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ILI, IN-DITCH AND PERMANENTLY INSTALLED TOOLS FOR STRESS/STRAIN IMAGING AND MONITORING

Dr. Neil J Goldfine, Mr. Todd M Dunford, Dr. Andrew P Washabaugh
JENTEK Sensors, Inc.
Marlborough, Massachusetts, USA

1 Abstract

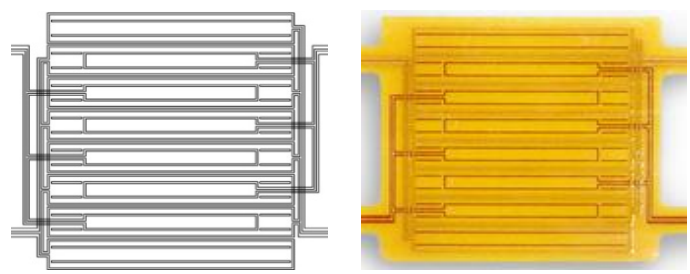
This paper addresses the ability to image and monitor strain (or stress), both residual and applied, in pipelines and other carbon steel structures such as risers and vessels. Strain (or stress) monitoring is needed to assess pipeline integrity after events such as ground motion, operating excesses, and prolonged operation in extreme environments. Three techniques are described: (1) an in-line-inspection (ILI) tool, (2) an in-ditch or above ground imaging method, and (3) a permanently installed approach. Each of these methods uses MWM sensors and MWM-Arrays to make non-contact measurements of the steel's magnetic properties, which are then correlated to strain (or stress) in the material. Since the method uses magnetic fields, it can operate through non-conductive materials such as coatings and insulation. This work was funded in-part by JENTEK Sensors, Inc., the Department of Transportation (DOT), and end users. The opinions in this paper are those of the authors and not the sponsoring agencies.

2 Introduction

This paper first describes the MWM and MWM-Array sensor constructs. The MWM construct, originally conceived in the 1980s at the MIT Laboratory for Electromagenetic and Electronic Systems, initially had a meandering drive. Newer versions of the MWM (see FIGURE 1), although still providing a periodic magnetic field, use a novel interdigitated rectangle drive construct and are now referred to simply as MWM sensors, not Meandering Winding Magnetometers.

The MWM-Arrays are not typically periodic for scanning/imaging configurations, but can be periodic for permanently installed applications, as described later. Example one and two dimensional MWM-Arrays are also described in the following, including MR-MWM-Arrays that use magnetoresistive sensing elements to measure through the pipe wall thickness when needed. Finally, descriptions of the Quadri-Directional Magnetic Stress Gage (QD-MSG) and Bi-Directional Magnetic Stress Gage (BD-MSG) configurations used for simultaneous multidirectional magnetic permeability measurement at a single point are provided. The description of these sensors is followed by brief descriptions of the unique instrumentation used to acquire data and provide input to the model-based multivariate inverse methods (MIMs).

The JENTEK MIMs are called Grid Methods (for 2-unknown solutions) and HyperLattice® methods (for 3 or more unknowns) and are used to rapidly convert the MWM and MWM-Array impedance measurements into properties of interest such as magnetic permeability, pipe wall thickness, and liftoff (where liftoff is defined as the proximity of the sensor to the first conducting or magnetic layer). These methods are also described in the following along with specific applications to stress (strain) measurement. In addition, results are described for several static and dynamic tests demonstrating the stress monitoring capability. These descriptions included (1) stress monitoring with temperature correction in a permanently installed mode, (2) stress monitoring on a pressure cycled pipe, along with crack growth monitoring, also in a permanently installed mode, and (3) stress imaging at mechanical damage sites in a pipeline segment. Finally, an in-line-inspection tool configuration is described, for internal stress imaging (and corrosion and crack detection).



(a) *(b)*

FIGURE 1: MWM (A) SCHEMATIC, (B) SENSOR. [1]

In the following, both stress and strain monitoring is referred to as stress monitoring. Referring to stress instead of strain is often met with discomfort since some believe that only strain can be measured (through displacement) and stress is inferred. However, since the MWM measures the directional components of the magnetic permeability which are directly influenced by applied and residual stresses in multiple directions (i.e. stresses in one direction affect the magnetic permeability in other directions), it is preferred by the authors to call these sensors stress gages and not strain gages (this is not meant to imply anything conclusively about stress/strain causality, merely to highlight the issue. One possibility is that changes in magnetic permeability are related to historical work done on the magnetic material – represented by the product of stress and cumulative strain).

3 MWM Sensors

FIGURE 1(a) provides a schematic of an MWM sensor and FIGURE 1(b) shows an actual sensor. The MWM was designed for absolute property measurements (e.g., electrical conductivity and magnetic permeability for metals), without calibration standards, using a model-based inverse method [2-5]. The MWM sensor consists of a periodic primary winding with a modified, patented, design [6] for creating the magnetic field and series-connected secondary rectangles for sensing the response [7]. The MWM sensors were designed to permit the sensor response to be accurately modeled, dramatically reducing calibration requirements (as described in ASTM guidelines E2338 and E2884 [8,9].

4 MWM-Arrays and MR-MWM-Arrays

MWM-Arrays can be one dimensional or two dimensional. One dimensional MWM-Arrays typically have a single rectangle drive winding construct or a dual rectangle winding construct as shown in the sensing elements can be either inductive coils (for MWM-Arrays) or magnetoresistive (MR) sensing elements (for MR-MWM-Arrays). FIGURE 3 shows a large flexible array with a dual rectangle drive construct (hidden in the photograph) and two rows of MR sensing elements. The MR sensing elements provide improved signal-to-noise at lower frequencies, enabling measurement of properties deeper into the material under test. This is useful for both stress monitoring and for detection of damage such as corrosion through layers. MR-MWM-Arrays are needed if inspection through aluminum weather jacketing is required for stress or damage measurement. Note that stress monitoring through weather jacket and insolation is possible using methods similar to those used for corrosion imaging, but with the nominal thickness assumed constant to allow the magnetic permeability to be estimated instead.

FIGURE 4 shows a photograph of a two-dimensional MWM-Array with a periodic drive. Similar sensors are available with a single row of sensing elements in a one-dimensional array. These periodic drive constructs are typically used in a permanently installed configuration [6,7].

FIGURE 5 provides the depth of penetration chart for a range of sensor constructs for steel materials over a range of magnetic permeability (assuming an electrical conductivity of 1MS/m which is typical for steel alloys). The depth of penetration represents the depth of the applied field penetration into the material and should not be used alone to represent the depth of sensitivity for stress estimation or damage detection. Since the electrical conductivity does not vary significantly with stress, it can often be assumed to be constant. However, both the conductivity and magnetic permeability vary with temperature and, assuming the conductivity is constant, can produce errors in the stress estimates if care is not taken.

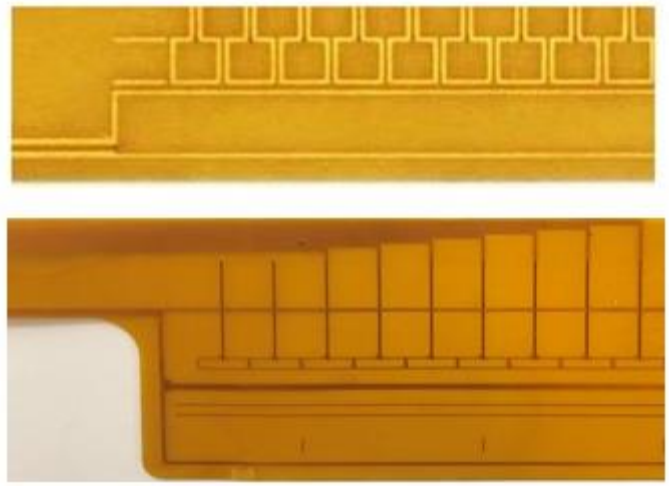


FIGURE 2: MWM-ARRAY (A) WITH A SINGLE RECTANGLE DRIVE WINDING CONSTRUCT, AND (B) WITH A DUAL RETANGLE DRIVE WINDING CONSTRUCT. [10, 11]

FIGURE 3: MR-MWM-ARRAY WITH A DUAL RECTANGLE DRIVE CONSTRUCT AND TWO ROWS OF MAGNETORESISTIVE (MR) SENSING ELEMENTS. [12]

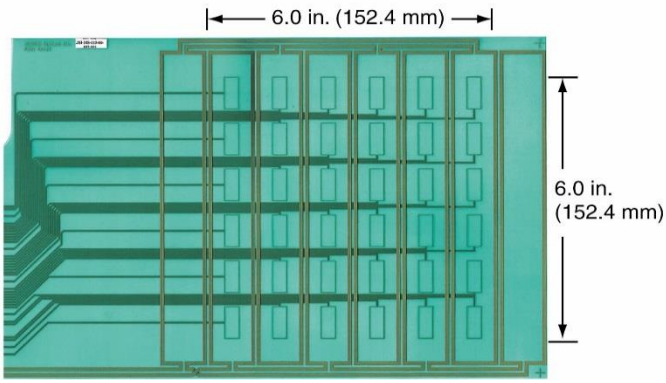


FIGURE 4: TWO DIMENSIONAL MWM-ARRAY WITH PERIODIC DRIVE WINDING CONSTRUCT AND 36 INDUCTIVE SENSING ELEMENTS. [13]

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

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

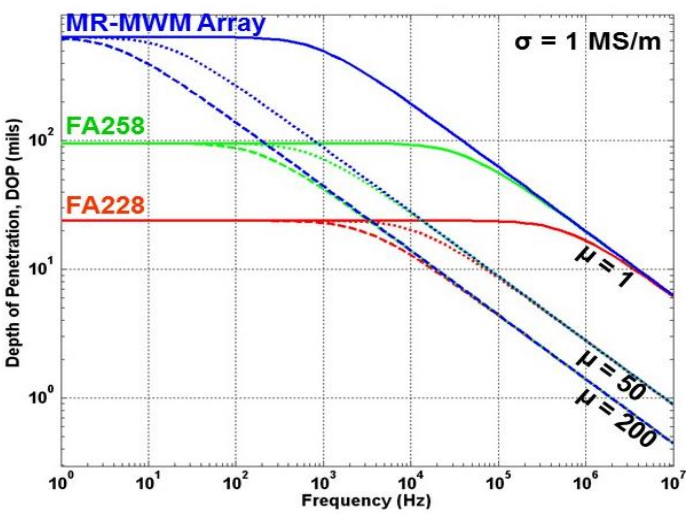


FIGURE 5: DEPTH OF PENETRATION CHART FOR VARIOUS DRIVE WINDING CONSTRUCTS, WHERE THE EFFECTIVE SPATIAL WAVELENGTH, λ, OF THE MWM OR MWM-ARRAY IS DERIVED FROM EITHER THE DRIVE TO SENSING ELEMENT GAP OR THE SPATIAL WAVELENGTH OF THE PERIODIC DRIVE CONSTRUCT OR A COMBINATION OF THESE DIMENSIONS. μ IN THE FIGURE IS THE RELATIVE MAGNETIC PERMEABILITY. 1 MIL= 0.001 INCHES. [13]

5 QD-MSGs

The MWM sensors or MWM-Arrays can provide a measurement of the magnetic permeability (independent of liftoff or other properties such as pipe wall thickness) under some practical circumstances. These measurements are directional in nature. In other words, the MWM or MWM-Array estimates the component of the magnetic permeability perpendicular to the longer drive winding segments within the sensor construct in the plane of the material under test. For practical applications, it is generally useful to normalize the measurement in one direction of interest by the measurement in another direction to remove material property variations that may not be of interest or to remove other stress components (e.g. from pressure in the pipe if that is known or not of concern). Furthermore, it is often useful to measure multidirectional or unidirectional magnetic permeability at multiple spatial locations (e.g. along a girth weld and in the axial direction away from the weld) to determine post weld heat treatment (PWHT) related residual stresses, before and after PWHT processing. For bending stresses and torque measurements, measurements at multiple locations are also of value to improve estimation accuracy and to reduce measurement noise.

The Quadri-Directional Magnetic Stress Gage (QD-MSG) (FIGURE 6) is a stack of four MWM sensors, with axes of sensitivity in four different directions (–45°, 0°, +45°, and 90°) [1,10]. A BD-MSG is simply a stack of two MWM sensors. The layout, orientation, secondary element size, and other geometrical properties are designed in a way that makes the sensing elements of one sensor insensitive to the magnetic fields generated by the primary windings of the other three sensors. This permits measurement of directional properties, such as conductivity or permeability, in four directions simultaneously and, although each sensor has a different off, the differences are known and can be accounted for by using the Grid Methods.

Arrays of these sensors (shown in FIGURE 7) have been used to demonstrate noncontact torque measurement capability on an unmodified main rotor shaft in a test cell at Boeing Rotorcraft Division [1]. These sensors might also be used for monitoring pipe or vessel stresses in either a permanently installed or scanning mode.

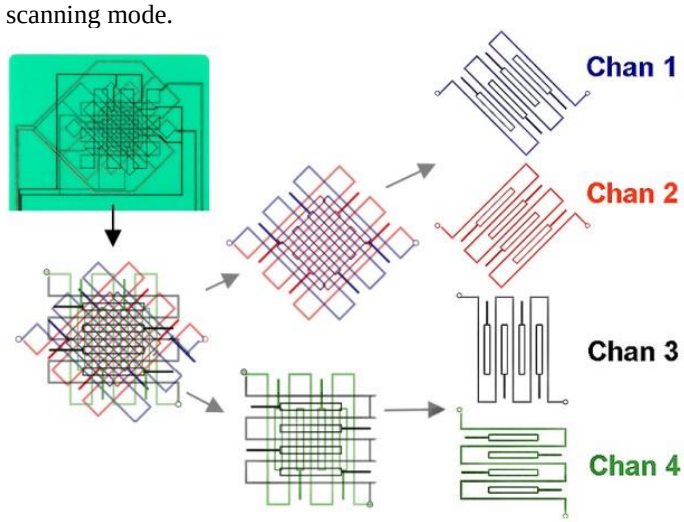


FIGURE 6: THE QUADRI-DIRECTIONAL MAGNETIC STRESS GAGE (QD-MSG™) IS A STACK OF FOUR DIRECTIONAL MWMS THAT PERMITS SIMULTANEOUS STRESS MEASUREMENT AT –45˚, 0˚, +45˚, AND 90˚. THIS PERMITS DETERMINATION OF AXIAL AND BENDING LOADS, AS WELL AS TORQUE. [1]

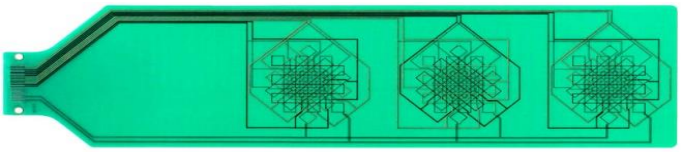


FIGURE 7: AN ARRAY OF THREE QD-MSG SENSORS USED FOR THE MAIN ROTOR SHAFT NONCONTACT TORQUE MEASUREMENT DEMONSTRATION. [1]

6 Parallel Architecture Instrumentation

FIGURE 8 and FIGURE 9 show JENTEK 7-channel and 39-channel parallel architecture instruments. Parallel architecture instruments are needed to enable simultaneous multidirectional sensing.

FIGURE 8: JENTEK 7-CHANNEL jET INSTRUMENT. [11]

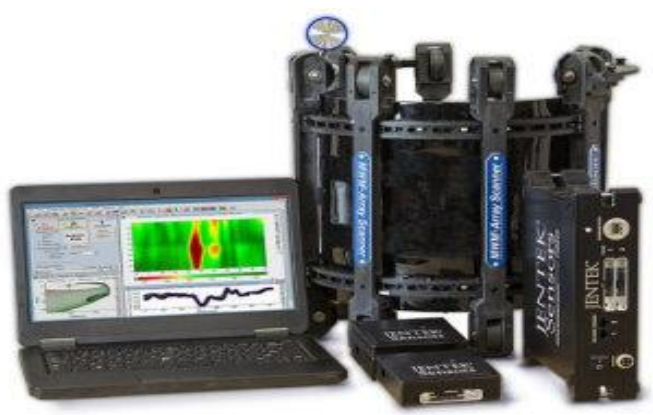


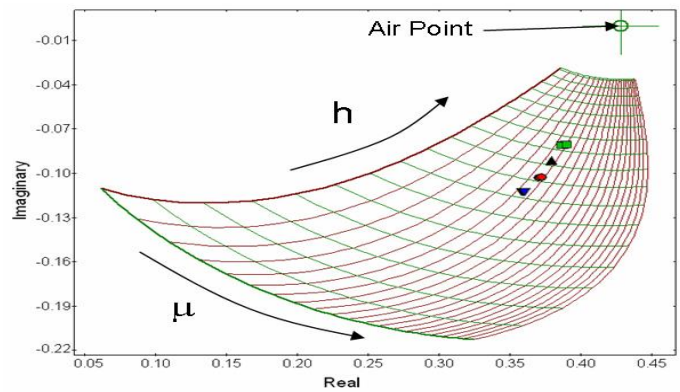
FIGURE 9: JENTEK 39-CHANNEL GRIDSTATION 8200 INSTRUMENT, WITH MR-MWM-ARRAY AND TWO MR PROBE ELECTRONICS UNITS. [11]

7 Grid and HyperLattice Methods

The Grid Methods use precomputed databases of sensor responses to represent the MWM or MWM-Array field interactions with the material under test. Grids are precomputed databases of sensor responses for estimation of two unknowns (such as magnetic permeability and liftoff). For three unknowns, the precomputed databases of sensor responses are called Lattices and for four or more unknowns, they are called HyperLattices [11].

FIGURE 10 shows a measurement grid for a two-unknown permeability/liftoff measurement. The measurement grid is generated using a model of the MWM field interactions with the neighboring material. The model used for this purpose was developed in the 1980s and refined over the years to enable extremely accurate representation of the MWM field interactions. The grid is generated once (off-line) and stored as a precomputed database for access by the GridStation® software. To generate the grid, all combinations of liftoff and magnetic permeability over the dynamic range of interest are input into the MWM models to compute the corresponding grid points. The visualization in FIGURE 10 includes lines of constant liftoff (h) and lines of constant magnetic permeability (μ). Calibration of the MWM and MWM-Arrays for all the data described in this paper was performed at the Air Point (Air Calibration) or at a single reference point on the part using the methods described in ASTM guidelines E2338 and E2884 [8,9].

To perform a permeability/liftoff measurement, first the real and imaginary parts of the complex transinductance (impedance/$j\omega$) are measured, at an instant in time, using JENTEK parallel architecture impedance instruments. It is important to make measurements at each sensing element simultaneously if the data is to be combined for dynamic stresses or if the sensor is moving relative to the material under test.



$$\text{Transinductance} = \frac{V_2}{j\omega i_1} = \text{Re}\left(\frac{V_2}{j\omega i_1}\right) + j\ \text{Im}\left(\frac{V_2}{j\omega i_1}\right)$$

FIGURE 10: MEASUREMENT GRID FOR LIFTOFF (h) AND MAGNETIC PERMEABILITY(μ) AT ONE APPLIED FREQUENCY F = ω/2π. NOTE THE TRANSINDUCTANCE REAL AND IMAGINARY PART ARE EASILY DERIVED FROM THE TRANSINDUCTANCE MAGNITUDE AND PHASE. THE COMPLEX REPRESENTATION IS PREFERRED FOR CALCULATIONS, BUT OFTEN THE MAGNITUDE AND PHASE PROVIDE A MORE INTUITIVE REPRESENTATION. EITHER CAN BE DISPLAYED IN THE JENTEK GRIDSTATION SOFTWARE. [1]

HyperLattice methods are for more than two unknowns and use more than one frequency or more than one sensor geometry or both. A typical application for stress measurement would be to determine pipe wall thickness, magnetic permeability, and liftoff as a three unknown method using a two or three frequency method and then estimating the magnetic permeability at multiple depths from the outer pipe surface using a second iteration on the MIM. FIGURE 11 shows a typical three unknown Lattice for permeability/liftoff/thickness estimation. Note that a HyperLattice is typically visualized as a series of Lattices (such as shown in FIGURE 11) that are plotted for different values of a fourth or fifth unknown, such as conductivity of the pipe wall.

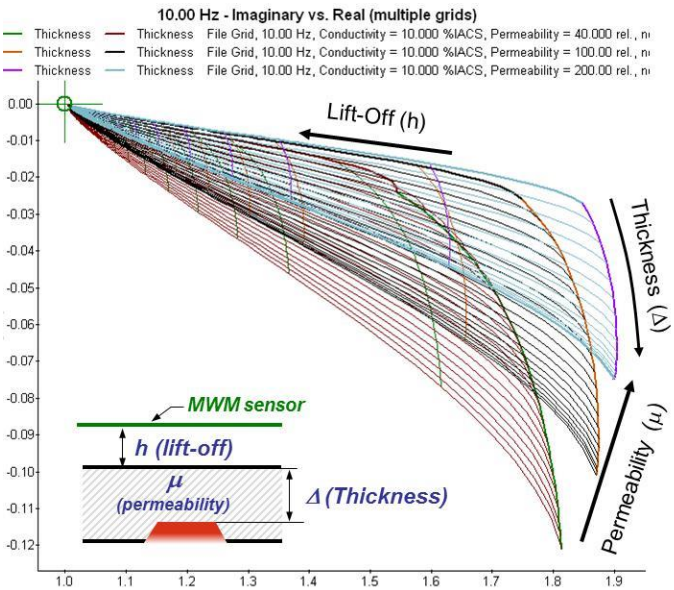


FIGURE 11: LATTICE FOR 3-UNKNOWN METHOD FOR PERMEABILITY/LIFTOFF/THICKNESS FOR A PIPE. [12]

8 Coupon Static Stress Testing

This section describes coupon tests at varied temperature along with correlation to stress (strain). FIGURE 12 provides a photograph of the setup with MWM-Arrays mounted to measure magnetic permeability in both the axial and transverse directions. FIGURE 13 shows the temperature sensitivity and the correlation plots between permeability and temperature. FIGURE 13 also shows that a monotonic response to stress can be obtained by combining the data in two orientations. This is needed since the response in the tensile direction peaks well before the stress reaches yield (see FIGURE 15). As the tensile stresses get higher, the transverse permeability measurement is used to obtain a monotonically increasing permeability response to stress variations.

FIGURE 12: PHOTOGRAPH OF TEST SETUP FOR OVEN TESTING OF BENDING COUPON WITH MOUNTED MWM-ARRAY FOR STRESS MONITORING. [13]

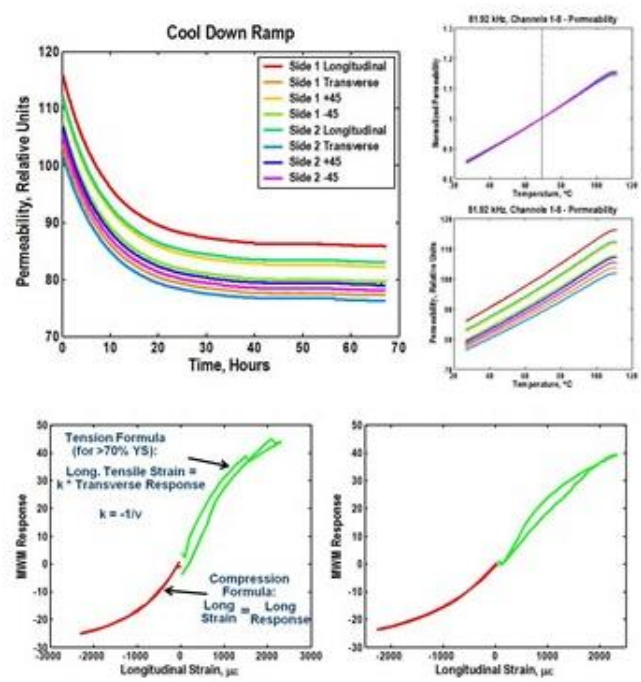


FIGURE 13:EXAMPLE RESULTS FROM OVEN TESTING OF BENDING COUPON WITH MOUNTED MWM-ARRAY FOR STRESS MONITORING. [13]

9 Dynamic Testing of a Pipe Segment

This section describes a stress monitoring capability demonstration on a pipe section where the pressure was varied using water pressure in a test at GDF Suez (now called Engie) under U.S. DOT funding. FIGURE 14 shows a photograph of the test setup for crack growth and stress monitoring at a mechanical damage site. The crack detection data has been presented previously [11]. FIGURE 15 provides a plot of the data taken using the installed MWM-Arrays at various locations along the axis of a gauged mechanical damage site.

FIGURE 14: PHOTOGRAPH GDF TEST SETUP FOR CRACK GROWTH AND STRESS MONITORING USING AN INSTALLED MWM-ARRAY AT A MECHANICAL DAMAGE SITE. [12]

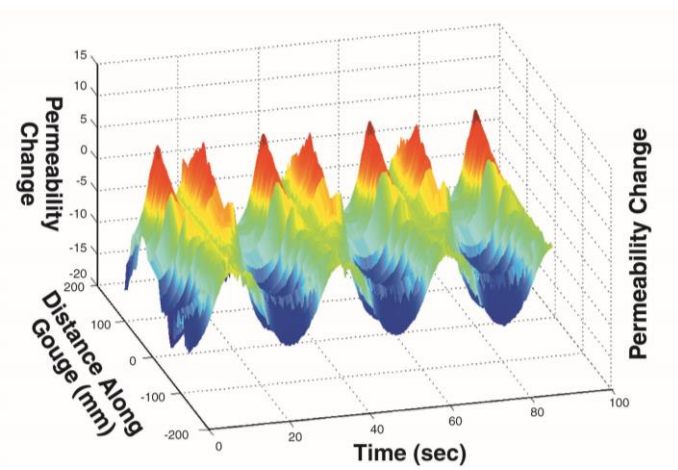


FIGURE 15: DYNAMIC STRESS DATA SHOWING VARIABLE PERMEABILITY AS THE PIPE SECTION PRESSURE IS VARIED CYCLICALLY OVER TIME. [12]

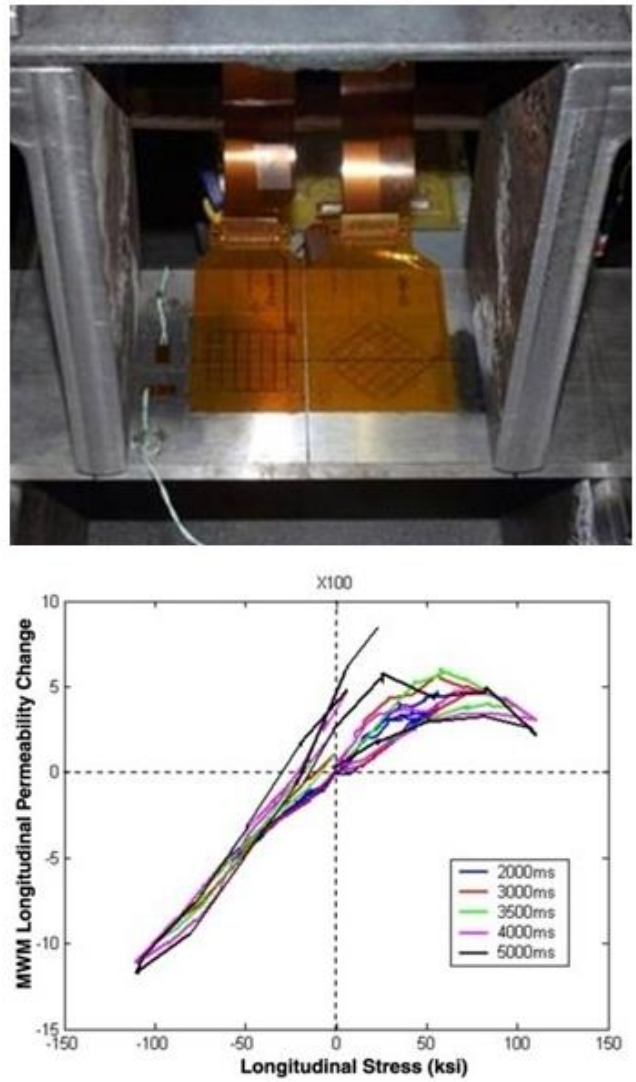


FIGURE 16: (TOP) STATIC TENSILE TEST COUPON DESIGN. (BOTTOM) COUPON TEST DATA SHOWING HOW THE PERMEABILITY VARIES WITH TENSILE AND COMPRESSIVE STRESSES. NOTE THAT THE RESPONSE PEAKS BEFORE YIELD IN THE TENSILE DIRECTION. THE VARIED COLORS REPRESENT REPEATED CYCLES OF THE STATIC (STEPPED) STRESS VARIATION. [12]

Note that using the method described in the previous section with bi-directional magnetic permeability measurements, the peak in the tensile stress response can be removed and a monotonic permeability vs stress relationship obtained (see FIGURE 13). It is valuable to note that the peak provides useful information about approaching tensile yield stresses that may be helpful in predicting sensitivity to stress corrosion cracking or overload conditions.

10 Residual Stress for Welds

FIGURE 17 provides the results of a measurement before and after post weld heat treatment for a sample with a nonvisible

mechanical damage site adjacent to the weld. The higher magnetic permeability region (dark blue to purple) indicates tensile stresses. This data was recorded with a 37-channel MWM-Array at a single frequency on an automated scanner. Note this data was presented by JENTEK previously [11].

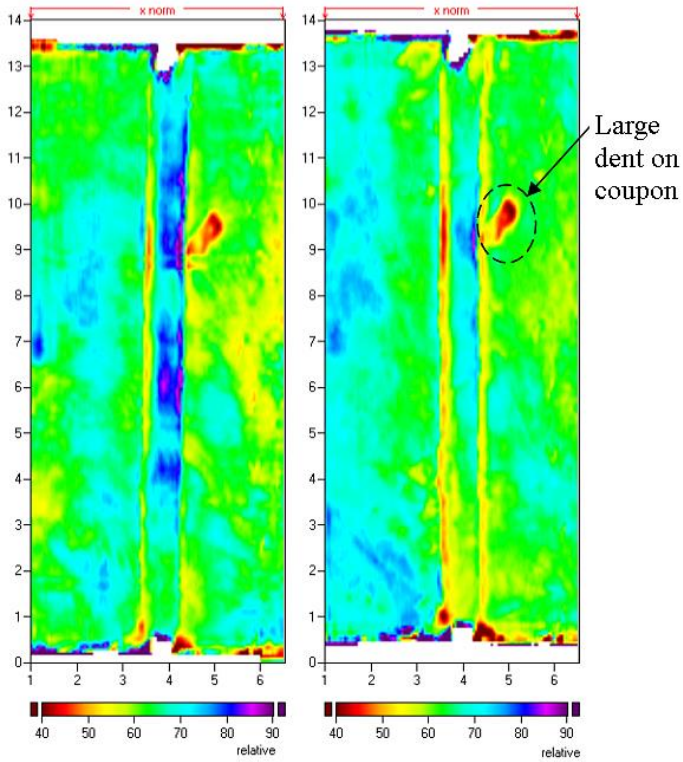


FIGURE 17: MAGNETIC PERMEABILITY MAP FOR A WELD WITH A MECHANICAL DAMAGE SITE, BEFORE AND AFTER POST WELD HEAT TREATMENT (PWHT). HIGHER PERMEABILITY CORRELATES TO HIGHER TENSILE STRESS. [12]

11 In-Line-Inspection (ILI) Tool

This section briefly describes an ILI tool for internal inspection of pipelines, with capability to map axial magnetic permeability and infer bending stress levels. FIGURE 18 shows the prototype tool. Two prototype tools where fabricated under DOT and other customer and JENTEK funding. An earlier version of these tools was successfully tested for imaging damage at the Pipeline Research Council International (PRCI) under DOT funding. Capability to image axial permeability was also demonstrated with suitability for stress imaging. This tool is not yet commercially available. Note that estimation of bending stresses is practical from axial permeability using apriori knowledge of spatial patterns in stress associated with bending loads. Estimating axial loads is more challenging, given typical variations in magnetic properties and the uniformity of the stress pattern.

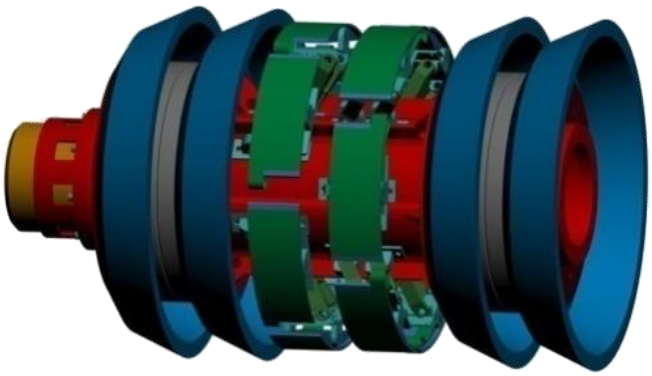


FIGURE 18: A SCHEMATIC OF A PROTOTYPE ILI TOOL FOR INTERNAL CORROSION IMAGING, CRACK DETECTION, AND STRESS ESTIMATION USING MWM-ARRAYS. [11]

12 Summary

This paper has presented example configurations and methods for stress/strain monitoring using novel magnetic field-based methods. Multidirectional methods enable stress monitoring and model based MIMs with MWM-Arrays and QD-MSGs make stress monitoring practical. The data presented provides examples of capability demonstrations performed over many years by the authors and others at JENTEK Sensors, Inc.

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