In-Line EMAT Ultrasonic Weld Inspection for ERW Tube Mill Using Guided Ultrasonic Waves

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INTRODUCTION: ERW PROCESS FOR TUBE AND PIPE

ERW tubes and pipes are cold formed from a strip of steel (skelp) pulled through a series of forming horizontal and vertical rollers positioned to gradually form the flat strip in to a tube which is then allowed to pass through the welding process.

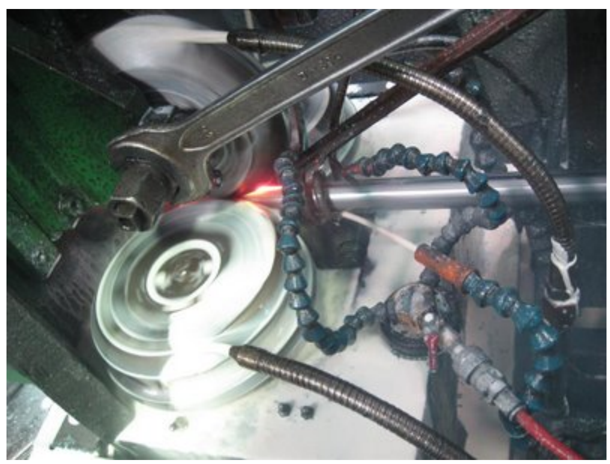
Figure 1: ERW Welder

In most mills, the position of the weld seam is the 12:00 o'clock position (Top). High frequency welders also require the use of an inside impeder; a cylindrical ferrite cylinder used to concentrate the induction current (heat) from the weld process on the skelp edges, especially on the inside circumference.

The impeder needs to be cooled with cooling fluid to extend its life and prevent overheating. Reverse flow impeders have the cooling liquid enter and exit the tool from the same non-welded side of the tube, thus presenting welded tube without coolant flowing through it.


Figure 2: Ernst Blissenbach GmbH ID Scarf tool

Attached to the impeder is normally an ID flash removal tool. Outside (OD) flash is removed by an external cutting tool as the tube leaves the weld zone while a take up spool collects the trimmed flash.

CURRENT INSPECTION METHODS

ERW pipes were first produced in the 1920's. In the 1960's manufacturers began to switch from low-frequency to high-frequency welding providing greater quality and mechanical performance.

Today, ERW tubes and pipes are a valid choice for the most demanding applications including Oil Country Tubular Goods (OCTG), and structural pipes.

In order to meet API and ASTM standards required for these applications, ERW tubes need to be subjected to strict nondestructive tests that will ensure that the product is free of defects as per the required specification.

Figure 3: OCTG ERW Tubes

The standard method for volumetric inspecting of ERW tube welds in production is ultrasonic testing using piezoelectric transducers. Albeit widely used in production, this method has two important shortcomings:

- It requires very precise positioning of sensors to address the weld
- It uses a liquid couplant to transmit the sound from the transducer into the material

Weld inspection with piezoelectric transducers is performed using shear vertical waves generated from refraction of a longitudinal wave. The sound generated in the piezoelectric sensor travels through a layer of water which serves both to couple the transducer to the part for sound transmission, and changes the angle of the original longitudinal wave to allow the generation of the shear wave used for inspection.

The shear wave energy generated in this process is carefully directed to the bottom and top of the weld using the "Half Skip/Full Skip Method" shown in Figure 4.

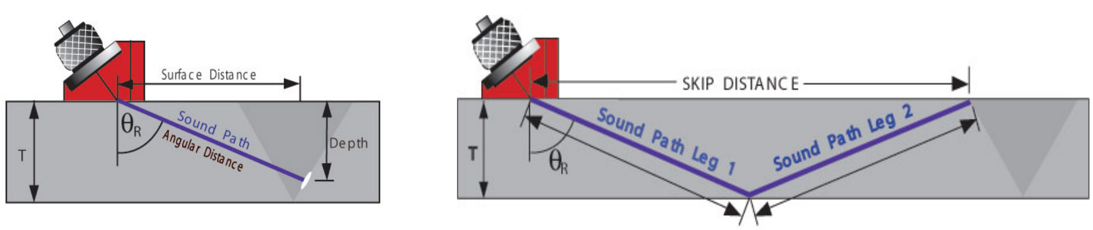

Figure 4: ID/OD weld defect detection
using "half skip/Full skip" method

The positioning of the probe/s with regards to the weld is extremely important to provide an adequate inspection. If these angles are properly maintained, the defects, when present, reflect sound back to the sensor and are detected by the equipment. However, even a minor change in the position of the transducers or the weld will result in a failed inspection. Even when the location of the weld is well known and controlled, spurious reflections from the root and crown due to poor flash removal, and the difficulty in detecting planar defects in the center of the weld are well-known limitations of this technique.

The couplant used for the transmission of sound also poses important constraints. First, the annulus of water around the pipe needs to be maintained with minimum turbulence and free of bubbles and contamination to avoid ghost reflections, which are difficult to ensure at speeds of over 1m/s. Second, all piezoelectric ultrasonic systems require that the weld is cooled before inspection to avoid the couplant from boiling off as it contacts the weld and Heat Affected Zone area. The solution to this problem is to locate the inspection station after the cooling trough, normally 20-40 feet after the welder.

While ERW is often referred to as "Straight Seam" pipe, in fact the best controlled ERW lines suffer from significant weld drift from the normal 12:00 o'clock position at welding, a condition that is worsened by the cooling process. By the time that the weld reaches the inspection station, its location is completely unknown, wreaking havoc with the requirement for precise location of the probes necessary for proper inspection.

Both manufacturers of equipment and users have invested a lot of time and effort trying to ameliorate the situation. Some manufacturers have used lasers, hall sensors and other means to track the location of the weld and adjust the ultrasonic equipment on-the-fly to inspect the weld area.

The latest phased-array systems use tens of channels on both sides of the welds (usually 32 on each side) to address up to 30º of the circumference in an effort to cover the wandering weld. These systems require very complex mechanics and electronics making them extremely costly to purchase and maintain, require constant calibration, and still suffer from the limitations inherent to the technique itself.

THE EMAT GUIDED WAVE SOLUTION

One of the most significant UT developments of the last 20 years is the advent of non-contact solutions that do not require coupling, such as Electro Magnetic Acoustic Transducers (EMAT), used for ultrasonic testing of metals.

While the sound in piezoelectric transducers is generated in the probe and transmitted into the part through the couplant, an EMAT induces ultrasonic waves into a test object with two interacting magnetic fields. A relatively high frequency (RF) field generated by electrical coils interacts with a low frequency or static field generated by magnets to generate a Lorentz force in a manner similar to an electric motor. This disturbance is transferred to the lattice of the material, producing an elastic wave.

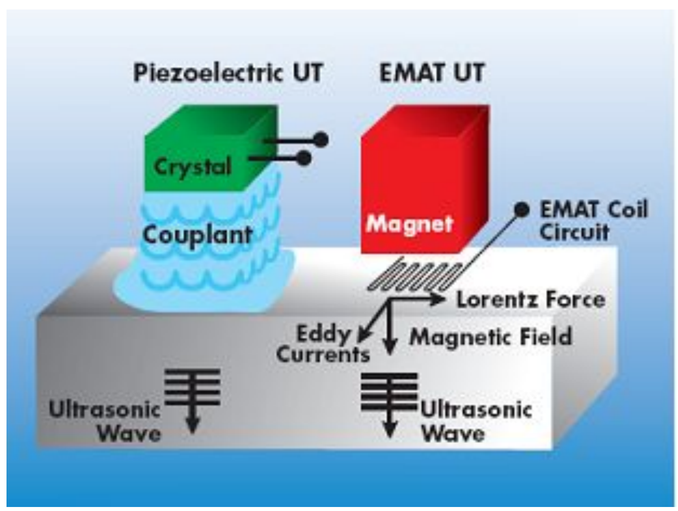

Figure 5: Comparison of piezoelectric and EMAT sound generation

In a reciprocal process, the interaction of elastic waves in the presence of a magnetic field induces currents in the receiving EMAT coil circuit. For ferromagnetic conductors, magnetostriction produces additional stresses that enhance the signals to much higher levels than could be obtained by the Lorentz force alone. Various types of waves can be generated using different combinations of RF Coils and Magnets.

EMATs have all the benefits of ultrasonic testing, but because the sound is generated in the part inspected, they enjoy some unique advantages for weld inspection:

- Dry Inspection (no couplant). Not having couplant permits more reliable readings (no couplant errors) and makes this technology easier to automate and integrate in production. High inspection speeds and high temperatures are also a fundamental advantage of EMATs. An EMAT system can inspect ERW tubes very close to the weld process, which increases the value of in-line inspection as a process control tool.
- Insensitive to Surface Conditions. EMATs are not sensitive to oxides, oil, water or uneven surfaces and can inspect through thin coatings of material.
- Unique Wave Modes. Because they do not depend on liquid to transmit the sound, EMATs can generate some guided wave modes that are not available or very difficult and impractical to generate with piezoelectric transducers

The main disadvantage of EMAT is the low efficiency of the transducer which requires high voltages and very precise electronic designs to generate and detect the signals. These disadvantages have become less relevant with the advent of new electronics and software that enhance complex signal processing in real time.

Inspection of thin welds using guided waves (SH and Lamb) has important benefits over the conventional approach. Whereas piezoelectric transducers use a shear vertical wave, with an angle of incidence between 30º and 60º from the perpendicular to the entry wall, an EMAT-generated guided wave fills up the full volume of the material and permits inspection of the full weld in one pass.

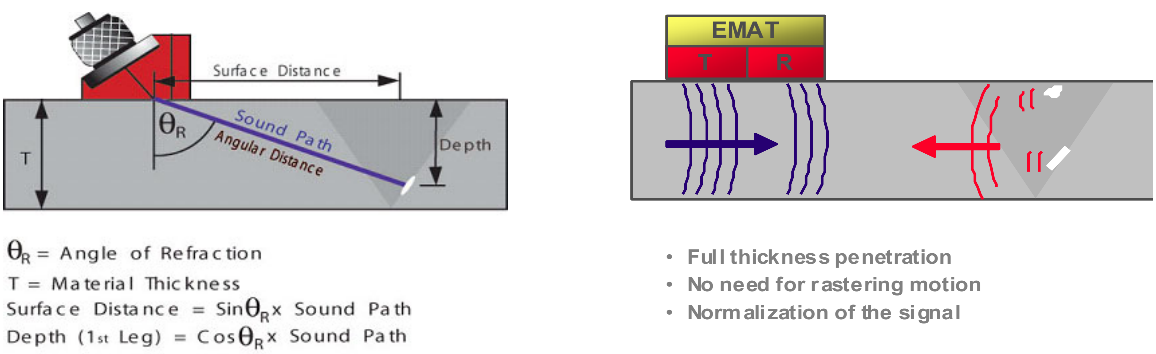

Figure 6: Comparison of angled beam and volumetric guided wave methods for Weld inspection

ADVANTAGES OF GUIDED WAVES FOR ERW WELD INSPECTION

- Guided waves fill the volume of the material independent of thickness enabling inspection of the entire weld
- Detects hook cracks, zipper welds, lack of fusion, and mismatch with greater reliability than angled beams
- Less sensitive to probe positioning, making it easier to automate and integrate into production
- By selecting the appropriate wave mode and threshold level, root and crown reflections from poor flash removal can be selectively ignored, thus making it less susceptible to false rejects
- In some cases, permits inspection of unscarfed welds
- Separate transmitter and receiver permits normalization of the signal for self- calibration
- Allows for up to 55º of weld drift with a minimum amount of sensors, resulting in cost-effective systems, easier to install and maintain

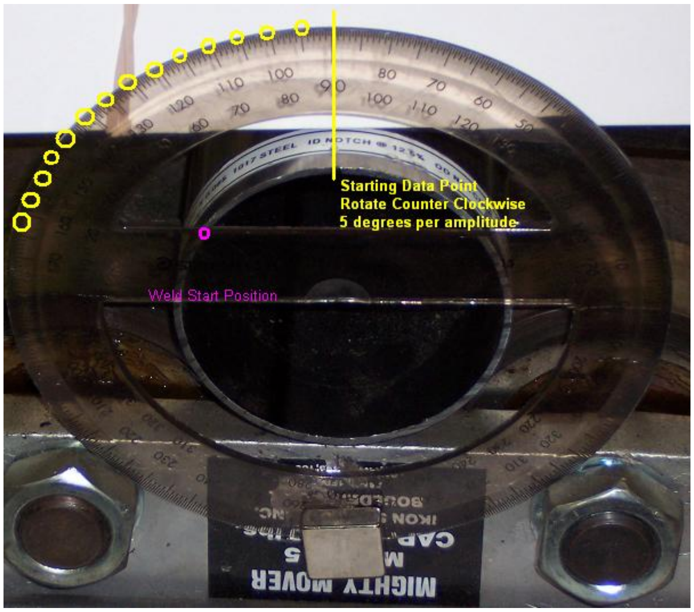

Figure 7: Lab Tests to Determine Sensitivity to Weld Drift

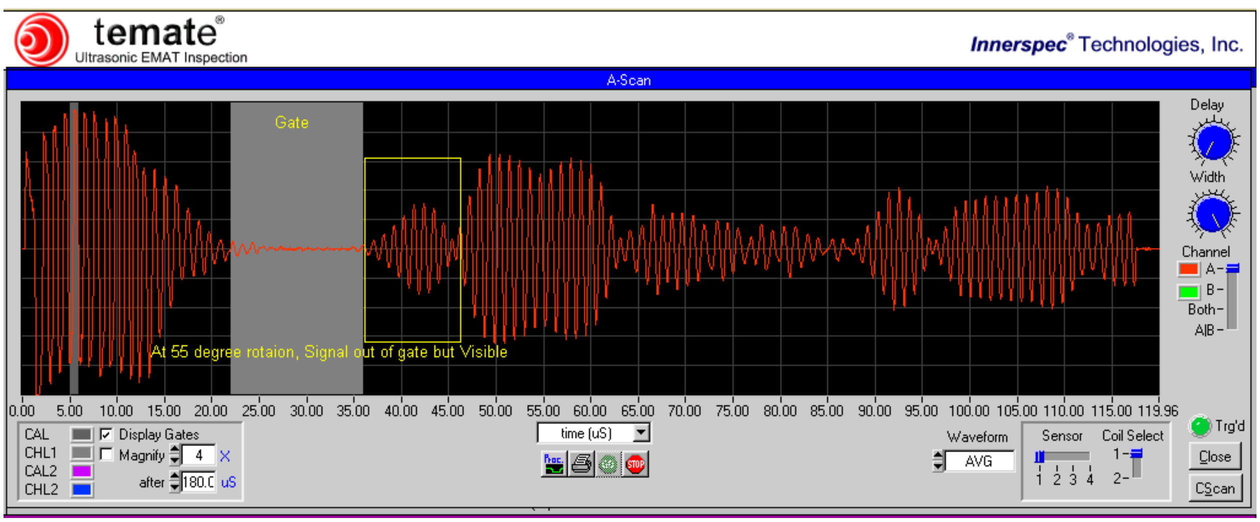

Figure 8: Defect is Easily Detected +/- 22.5º from the Normal

THE temate® Si-BW FOR ERW INSPECTION

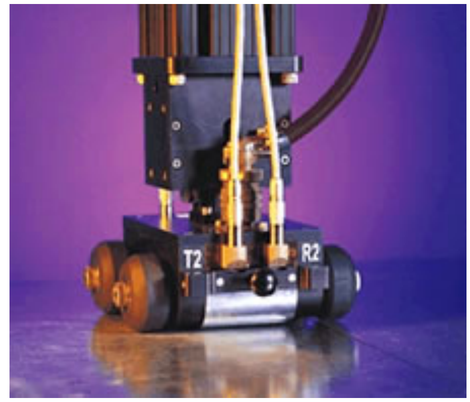

Figure 9: temate® Si-WB Sensor for Inspection of Tailor Welded Blanks

Innerspec Technologies has recently developed a complete solution for ERW inspection based on its **temate® Si** platform.

This platform has now been used for over 14 years for inspection of thin welds with guided waves in the steel, automotive and manufacturing industries. With over 100 in-line systems currently in operation, it has become the industry-standard for a number of applications where a reliable, easy-to-use, and fully automated volumetric inspection system is required.

While all the systems under this platform share the electronics and software, the sensors are uniquely developed for each application. The development of the sensors requires a rigorous understanding of the theory and practice of the complex field of guided waves. For this purpose, Innerspec Technologies has developed a full range of proprietary software tools that permit rapid development with optimized results.

SENSOR DEVELOPMENT

The first step in sensor development is to determine the guided wave mode most adequate for the type of defects to be detected. Symmetric and asymmetric lamb waves, and shear horizontal waves have unique characteristics that make them better suited for different situations.

The next step is to determine the tube specifications including its chemistry, mechanical characteristics, diameter and wall thickness to calculate the group velocity and phase velocity curves (dispersion curves). The dispersion curves will determine the wavelength and frequency required to excite each particular mode.

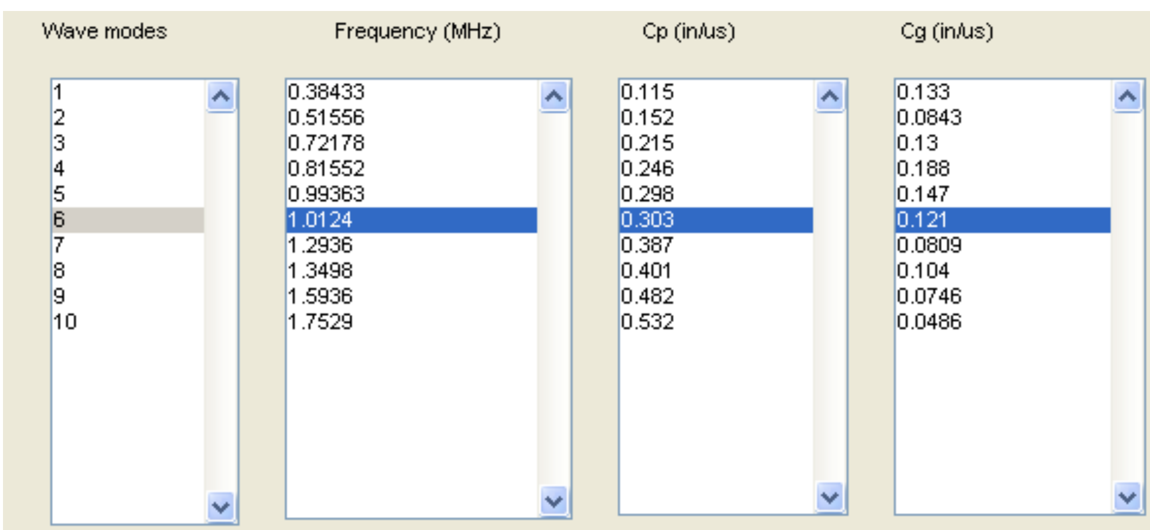

Figure 10: Wave order mode analysis after entering all required data

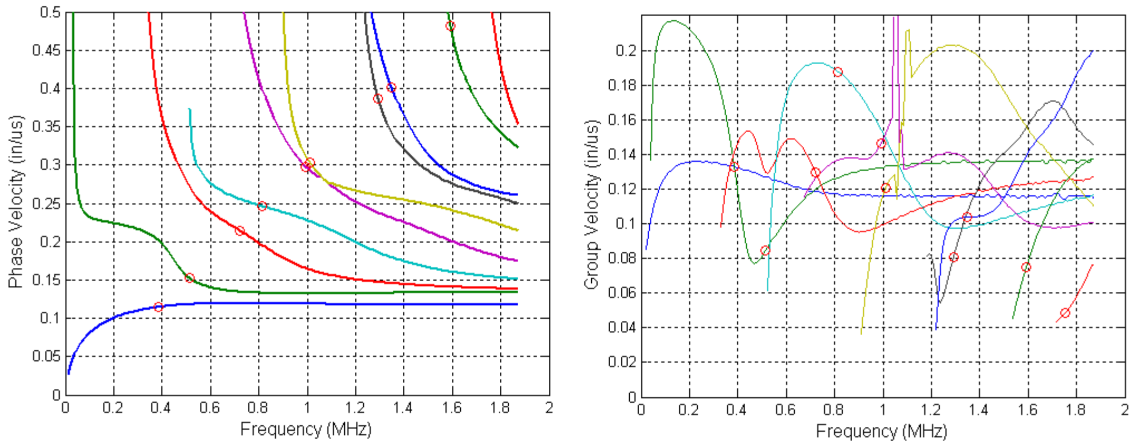

Figure 11: Phase and Group Velocity Curves used to determine frequency and wave mode for a particular tube diameter and wall thickness

Using data displayed from group and phase velocity curves, candidate wave modes are qualified based on their OD sensitivity (Mode 1) and ID sensitivity (Mode 2). The goal is to find a mode in which the particle motion provides near equal amplitude for mid-wall, ID and OD surfaces.

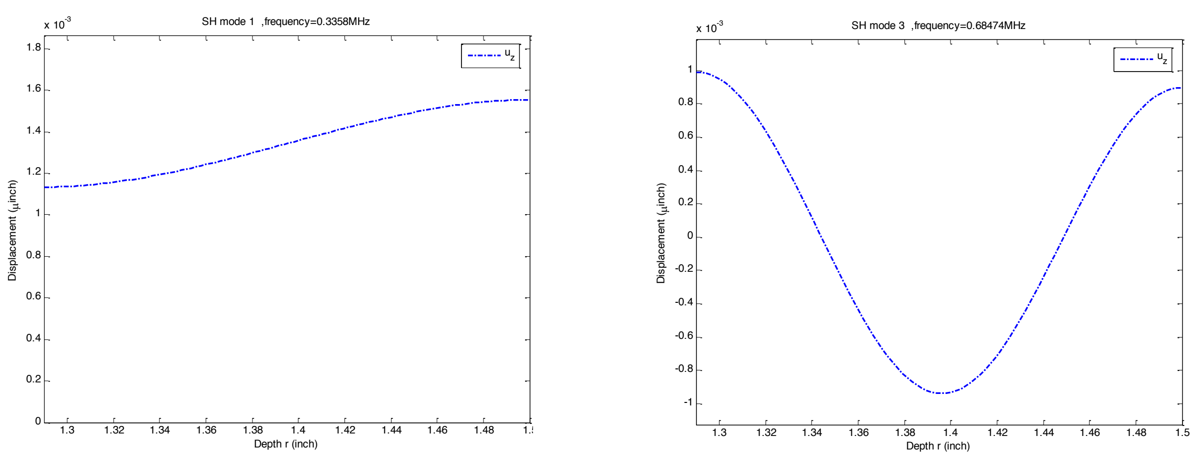

Figure 12: Wave displacement curves. Left Curve shows good amplitude of particle motion from ID to OD surface. Right Curve shows good ID and OD amplitude but poor Mid-wall sensitivity (A flat line represents equal sensitivity across the weld)

Prior to the manufacture of the sensor, Finite Element Modeling is used to corroborate that the sensor does indeed react to the defects as expected.

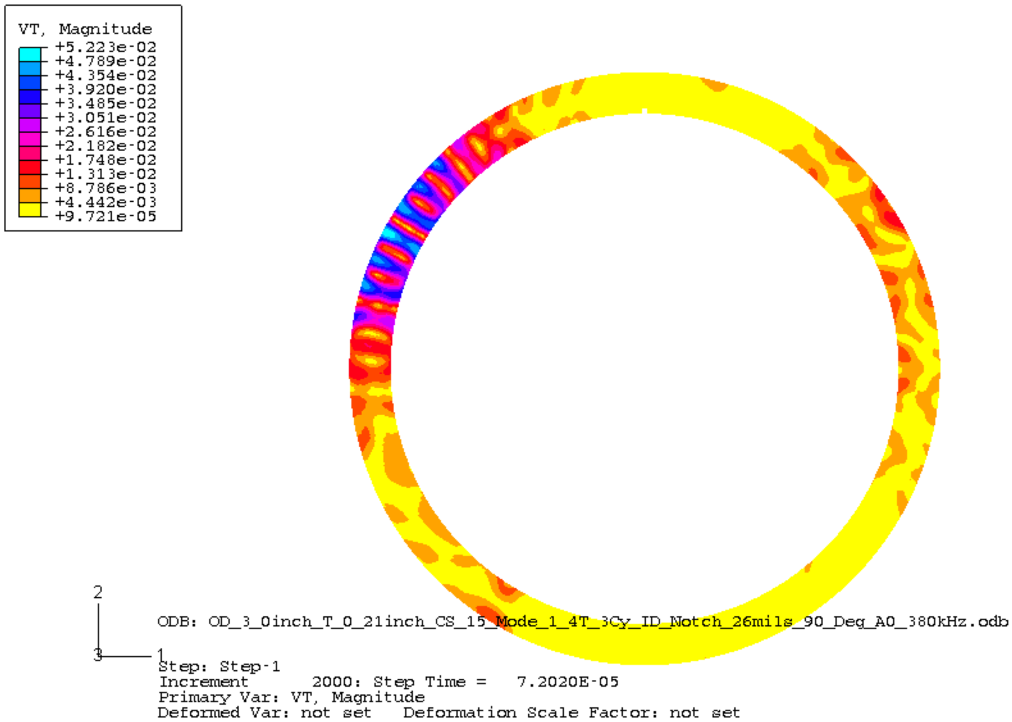

Figure 13: FEMM Modeling of Wave Mode Reacting to ID, OD and Mid-Wall Defects to Verify Sensitivity

The final step is to manufacture of the sensor and perform empirical tests on calibrated samples (Figure 14).

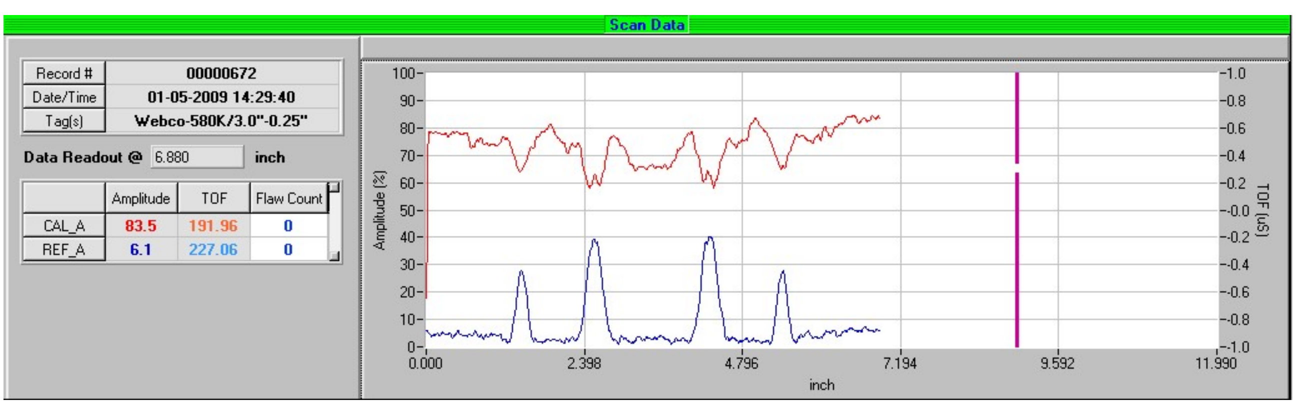

Figure 14: Tube with ID/OD Notches Verifies Modeling

Since each thickness and diameter has different propagation characteristics, the process needs to be repeated for each tube combination. The following is an actual table prepared for an installation in North America with tubes ranging from 1” to 4” OD, and 0.060” to 0.300” in thickness.

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Thickness	1	1.25	1.5	1.625	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
0.06	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.065	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.07	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.075	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.08	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.085	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.09	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.095	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
0.105	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.11	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.115	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.12	A2	A2	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.125	A2	A2	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.13	A2	A2	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
0.135	A2	A2	A2	A2	A2	C1	C1	C1	C1	C1	C1	C1	C1	C1
0.14	A2	A2	A2	A2	A2	C1	C1	C1	C1	C1	C1	C1	C1	C1
0.145		A2	A2	A2	A2	C2	C1	C1	C1	C1	C1	C1	C1	C1
0.15		A2	A2	A2	A2	A2	C1/C4	D1	D1	C1	C1	C1	C1	C1
0.155		A2	A2	A2	A2	A2	C1/C4	D1	D1	C1	C1	C1	C1	C1
0.16		A2	A2	A2	A2	A2	C4/C1	D1	D1	C1	C1	C1	C1	C1
0.165		B2	B2	A2	A2	A2	C4/D1	D1	D1	D1	C1	C1	C1	C1
0.17		B2	B2	A2	A2	A2	C4/D1/C1	D1	D1	D1	C1	C1	C1	C1
0.175		B2	B2	A2	A2	A2	A2	D1	D1	D1	D1	D1	C1	C1
0.18		B2	B2	A2	A2	A2	A2	D1	D1	D1	D1	D1	C1	C1
0.185		B2	B2	B2	A2	A2	A2	D1	D1	D1	D1	D1	D1	C1
0.19		B2	B2	B2	A2	A2	A2	D1	D1	D1	D1	D1	D1	C1
0.195		B2	B2	B2	A2	A2	A2	D1	D1	D1	D1	D1	D1	C1
0.2		B2	B2	B2	B2	A2	A2	D1	D1	D1	D1	D1	D1	C1
0.205			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.21			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.215			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.22			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.225			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.23			C2	B2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.235			C2	C2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.24			C2	C2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.245			C2	C2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.25			C2	C2	B2	A2	A2	A2	A2	A2	A2	E1	E1	D1
0.255				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.26				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.265				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.27				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.275				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.28				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.285				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.29				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.295				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1
0.3				C2	B2	B2	B2	B2	B2	A2	A2	E1	E1	E1

Figure 15: Example Product Range and EMAT Selection

In this case, this manufacturer is able to inspect up to 686 different tube combinations using only 8 different EMAT coils.

Setting up the equipment for each tube is done automatically by downloading from the line PLC the type of tube being welded.

CONCLUSIONS

The traditional ultrasonic systems based on piezoelectric transducers have well-known limitations for in-line inspection of ERW tube welds.

Manufacturers have tried to bypass the intrinsic restrictions of this technique by placing the equipment in less desirable locations, and by implementing complex systems that are expensive to purchase, difficult to maintain, and still do not address its fundamental shortcomings.

Leveraging on a proven platform, and using the latest theoretical advances and modeling tools in the field of guided waves, Innerspec Technologies has developed a new approach that successfully addresses all these limitations.

This new ERW weld inspection system based on EMAT-generated guided waves permits location of the equipment wherever is more convenient for the mill and the process. The equipment has been tested to meet API and ASTM standards, and it is easier to install, maintain and operate than the latest piezoelectric systems, at a fraction of their cost.

ACKNOWLEDGMENTS

I wish to thank my colleagues all the employees and management of Innerspec Technologies, especially our Research and Development department for their diligent work in developing the necessary and unique tools and modeling software to allow the use of guided wave ultrasonic EMAT inspection to be exploited in ERW Tube Weld Inspection.