Inspection of lamp posts and other non-accessible areas with EMAT Medium-Range Guided Waves

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Abstract

Corrosion detection is an essential part of a strategy to protect critical assets exposed to the environment. This activity becomes especially challenging when a section of the object being inspected is buried, covered, or coated, as it frequently happens with lamp posts, underground road crossing pipes, tanks, and insulated tubes. The frequent presence of moisture and chemicals in the non-accessible areas can aggravate the degradation process making their inspection a matter of vital importance.

In this paper, a new Medium-Range Guided Wave technique is presented as a reliable and efficient solution to perform volumetric inspection in non-accessible areas.

1. Introduction

Lamp posts and other street poles and columns are some of the most common civil structures in our cities, providing signalling and illumination for modern life. The continuous exposure to the environment results in corrosion and fatigue cracking that creates a progressive deterioration of the structural condition of the poles. These poles have typically a life span of up 40 years, which can be dramatically shortened by weather and contamination. For example, at ground level and just below there is an environment rich in moisture, chlorides, and oxygen that promotes the corrosion of the steel structure precisely in the area of maximum stress. The loss in metal thickness caused by corrosion can cause sudden failure and significant damage to people and surrounding property.

Although collapsing of street poles is not frequent, some have resulted in fatalities and property damage with significant costs. After many accidents concerning corroded lamp posts (San Francisco, 2015) [1], many municipalities have now imposed strict regulatory requirements for their inspection at periodic maintenance intervals to ensure long-term structural integrity.

Figure 1. Lamp post collapse due to corrosion in San Francisco (2015)

While wall loss thickness measurement is an efficient way of identifying corrosion on the exposed areas, this is not possible when direct access to the wall of the pole is not possible. Medium-Range EMAT Guided Waves traveling g in the axial direction are presented as a solution to detect and localize corrosion in exposed and buried, non-accessible sections of the posts.

The two most common methods for in-service inspections with Guided Waves are Long Range Ultrasonic Testing (LRUT) and Medium Range Ultrasonic Testing (MRUT). LRUT is used almost exclusively for pipe inspection in reflection mode. LRUT works at low frequencies (≈50 kHz) and permits covering long distances (up to 50-100 m) from a fixed ring of sensors. The drawbacks of this methodology are the large dead zone of approximately 3 meters (in each direction), the cost and complexity of the equipment, and its inability to inspect structures other than pipes. MRUT is a complementary technique that can be used in both attenuation and reflection modes to cover shorter distances (0.1-3m) with greater detection sensitivity and resolution. The MRUT sensors are typically mounted on hand-held or motorized scanners and driven around or along the pipe, plate, railhead or structure to cover long stretches at fast speeds. The higher frequencies used on MRUT (from 100 kHz to 1.5 MHz) provide up to 10 times more sensitivity to defects than LRUT, while the shorter distance to the target area greatly improves the probability of detection and resolution.

Innerspec Technologies introduced the first portable MRUT instrument and scanner with lamb waves in 2010, and has recently added the MRUT MS Scanner to improve inspection in buried pipes, posts, and other structures using Shear Horizontal waves generated with a magnetostrictive strip. This novel and patented technique permits inspection of inaccessible areas with an unprecedented degree of sensitivity and resolution.

2. Magnetostrictive transducers

Magnetostriction is a phenomenon involving a magnetization process and dimension/shape change in ferromagnetic materials [2-3]. A magnetostrictive material which is subject to a magnetic field, changes its length as shown in Figure 2a (Joule Effect). The change in length experienced is due to the rotation of the magnetic domains in the ferromagnetic material. The inverse effect by which a ferromagnetic material induces a magnetic field when its length changes, is called "Villari Effect".

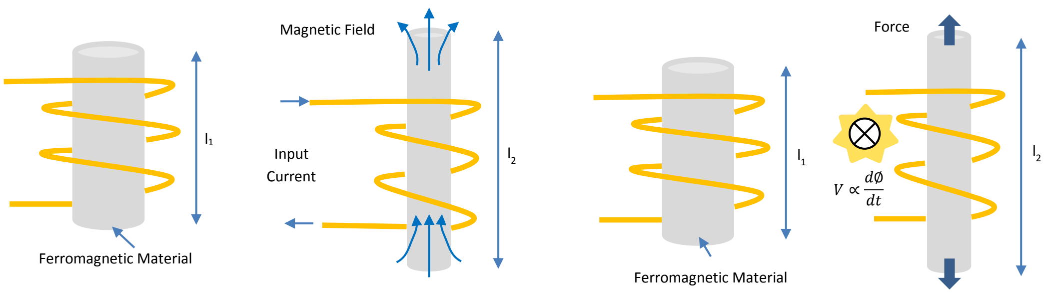


Figure 2. a) Joule Effect (Direct Magnetostrictive Effect), b) Villari Effect (Inverse Magnetostrictive Effect)

A third effect to take into consideration is the "Wiedemmann Effect" which is based on the two aforementioned situations. It is experienced by ferromagnetic materials which are subject to static and dynamic magnetic fields orthogonal to each other. Under these conditions, a shearing deformation is developed in the material.

The magnetostrictive effect has been successfully used for generation and measurement of guided waves for decades. For pipe inspection, different configurations of Magnetostrictive Patch Transducers (MPTs) have been developed to measure torsional waves inside a pipe. The transducer utilized by Innerspec, which will be further described in the following sections, induces a dynamic magnetic field on the magnetostrictive patch (strip) through a coil, whereas the static magnetic field is induced by pre-magnetization (rubbing the strip with a permanent magnet). By adhering the magnetostrictive strip to the part inspected, the transduction efficiency of the strip permits efficient generation of guided waves on nearly any material, conductive or not.

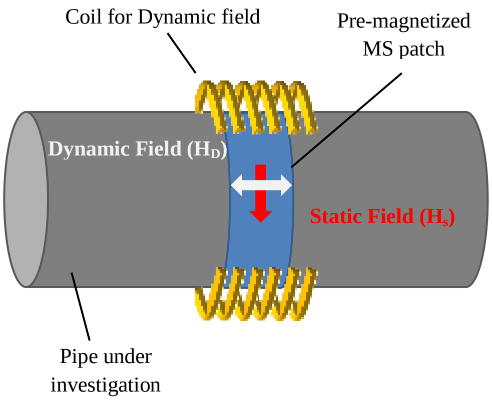


Figure 3. Magnetostrictive patch transducer to measure torsional waves inside a pipe

Figure 3 depicts the transduction mechanism to generate mechanical waves in a ferromagnetic material using the Wiedemmann Effect. The combination of both dynamic magnetic (H_D) and static bias magnetic (H_S) fields, results in the strain of the material [4].

The most common types of volumetric guided waves are Shear Horizontal (SH) and Lamb. SH ultrasound waves are polarized in-plane with respect to a reference interface (typically a sample surface). SH waves have several properties that are beneficial for non-destructive testing (NDT). For instance, an SH wave with parallel polarization to a boundary is reflected without mode conversion. When SH waves are polarised perpendicular to the direction of the grain (e.g. dendritic grain structure in an austenitic weld) they propagate through the grain with less reflection, beam steering, and attenuation than any other wave mode (L, Shear Vertical or Lamb), and they do not mode-convert upon interaction with a defect that extends parallel to the welding direction [5-6].

SH waves are also more appropriate than Lamb (assymetric) waves in all those applications were surrounding liquids and coatings may cause attenuation, as the particle motion happens mainly in the horizontal plane. Of all the SH wave modes (Figure 4), the work described in this manuscript only uses the lowest order SH_0, which has a symmetric non-dispersive behavior that permits easier interpretation. The fact that it can be generated in a broad range of thicknesses using the same excitation frequency becomes an additional advantage.

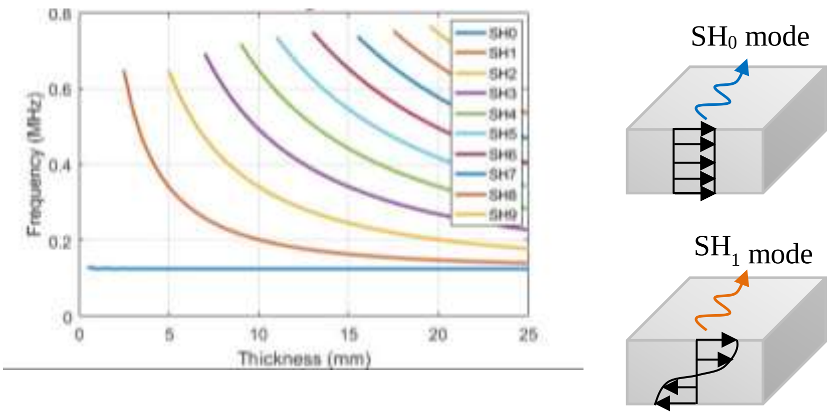


Figure 4. a) Dispersion Curves of the Shear-Horizontal (SH) wave, b) Mode shape of the lowest two modes (SH_0 and SH_1)

3. MRUT MS Scanner

The MRUT MS (magnetostrictive) Scanner is the most appropriate tool for defect detection under supports, buried structures, and other non-accessible areas. The SH wave mode is generated in a magnetostrictive strip which has been firmly attached to the surface of the material as depicted in Figure 5a. Detection is accomplished by pre-magnetizing the strip, and moving the scanner along (Figure 5b). In Pulse-Echo (PE) configuration, the receiver coil is used both as transmitter and receiver, and defects are detected and assessed by the amount of sound that they reflect back. With regards to efficiency, the magnetostrictive strip developed by Innerspec can provide up to 20dB more ultrasonic energy than more conventional Lamb transducers.

For inspection of lamp posts or buried pipes, the strip is attached around the circumference of the part under investigation. In this configuration, SH waves travel along the axis of the pipe in both directions. This new scanner together with a two-channel instrument permit sending guided waves in one direction, thus avoiding reflections from the opposite section and facilitating the interpretation of results. The MRUT MS Scanner is suitable for the inspection of pipes and structures from 4.5 inches (114mm) OD to flat.

Figure 5. a) MRUT MS Scanner placed on a MS Strip b) Circumferential scanning sending the waves both sides in the axial direction

The magnetostrictive strip can be adhered permanently if the aim is to monitor the structure regularly, or temporarily for one time inspections. Before attaching the strip, the surface needs to be assessed and prepared, removing any loose scale and surface contaminants so bonding is optimized. The strip can be applied on painted or oxidized surfaces as long as the paint or oxide layer are tightly adhered. The magnetostrictive strip can be attached using a tensioner (Figure 6a), double-sided tape (Figure 6b), or epoxy (Figure 6c).

Table 1. Comparison of the three available attachment methods

	Tensioner	Double-Sided tape	Epoxy
Temperature	High temperature (<200°C)	Temperatures below 80°C	Temperatures below 80°C
Time to inspection	Immediate	Immediate	Curing time (15 min)
Sensitivity	Low-Medium	Medium-High	High

The tensioner typically provides worse sensitivity results due to the looser bonding of the strip to the part. This technique is recommended only when the application requires working at high temperatures (up to 200°C). The strip is placed around the pipe and both sides of the strip are fastened with the clamping plates shown in Figure 6a. Tension is applied by tightening the top screw on the tensioner. After attaching the magnetostrictive patch the inspection can start.

The second method uses double-sided tape to bind the strip to the pipe. It is an easy and quick attachment method that provides good sensitivity results. This option is not designed for operating at temperatures higher than 80°C.

Gluing with epoxy typically provides the most reliable results and highest signal-to-noise due to the solidity of the binding in comparison with the other methods. It cannot be used in applications where working temperatures are higher than 80°C. Once the epoxy has been applied, the strip needs to be wrapped and left to cure for 15-30 minutes after which it is ready for inspection. The tests presented in this paper were all performed using this method.

a) b) c)

Figure 6. MS Strip attachment: a) Tensioner, b) Double-sided tape, c) Epoxy

The MRUT MS Scanner has a dead zone of 10-15 cm which permits performing the inspection in very close proximity to the area of interest. Moreover, by inspecting closer to the defects and higher frequencies, the detection and resolution are typically 10 times better than with Long-Range UT techniques. MRUT is frequently used to complement LRUT and provide greater probability of detection and resolution in short ranges or in non-accessible areas where the deployment of the LRUT rings is not feasible [7].

4. Corrosion detection of non-accessible areas. Case Study

Innerspec performed experimental trials on a lamp post mock-up to demonstrate the capabilities of the new MRUT MS Scanner for corrosion detection in non-accessible areas (buried sections). The dimensions of the pipe utilized for the mock-up are depicted in Table 2.

Table 2. Pipe features (EN-10297, Quality E355/S355J2H)

Length		Outer Diameter		Wall Thickness	
mm	**Inch**	**mm**	**inch**	**mm**	**inch**
2400	94.5	219.1	8.6	8	0.31

Defects were machined around two circumference sections, located at 600 mm (defects D1.A and D1.B) and 300 mm (defects D2.A and D2.B) from the pipe's toe. These four defects have a spherical bottom shape machined with a ball-end milling tool, and they are located 90° apart from each other. Machined defects D1.A and D1.B are shown in Figure 7a and Figure 7b respectively. Further details regarding the drill diameter and the depth are provided in Figure 8.

a) b)

Figure 7. Machined defects D1.A and D1.B

Test points were chosen at 700 and 1200 mm from the left-hand side of the pipe (Figure 8). A magnetostrictive strip was attached to the pipe at those locations using epoxy to ensure optimum binding between the strip and the test piece.

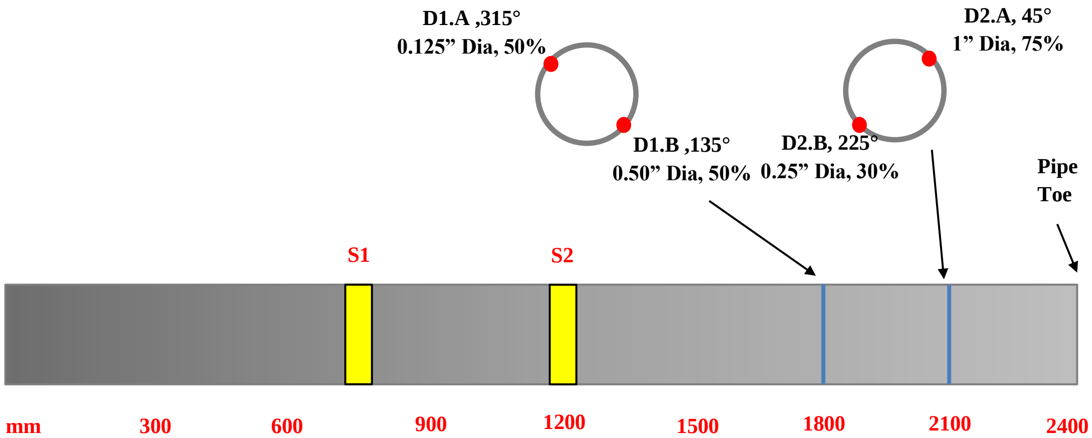


Figure 8. Lamp post mock-up unburied

The MS Scanner was tested on three different scenarios. First, the full pipe from Figure 8 was tested in the air so the results can be used as a reference. The second test involved burying a 900 mm section (including both rings of defects) of an identical pipe in soil of compacted clay. The third test was performed on the original pipe buried in concrete. Buried mock-ups are shown in Figure 9b and Figure 9c.

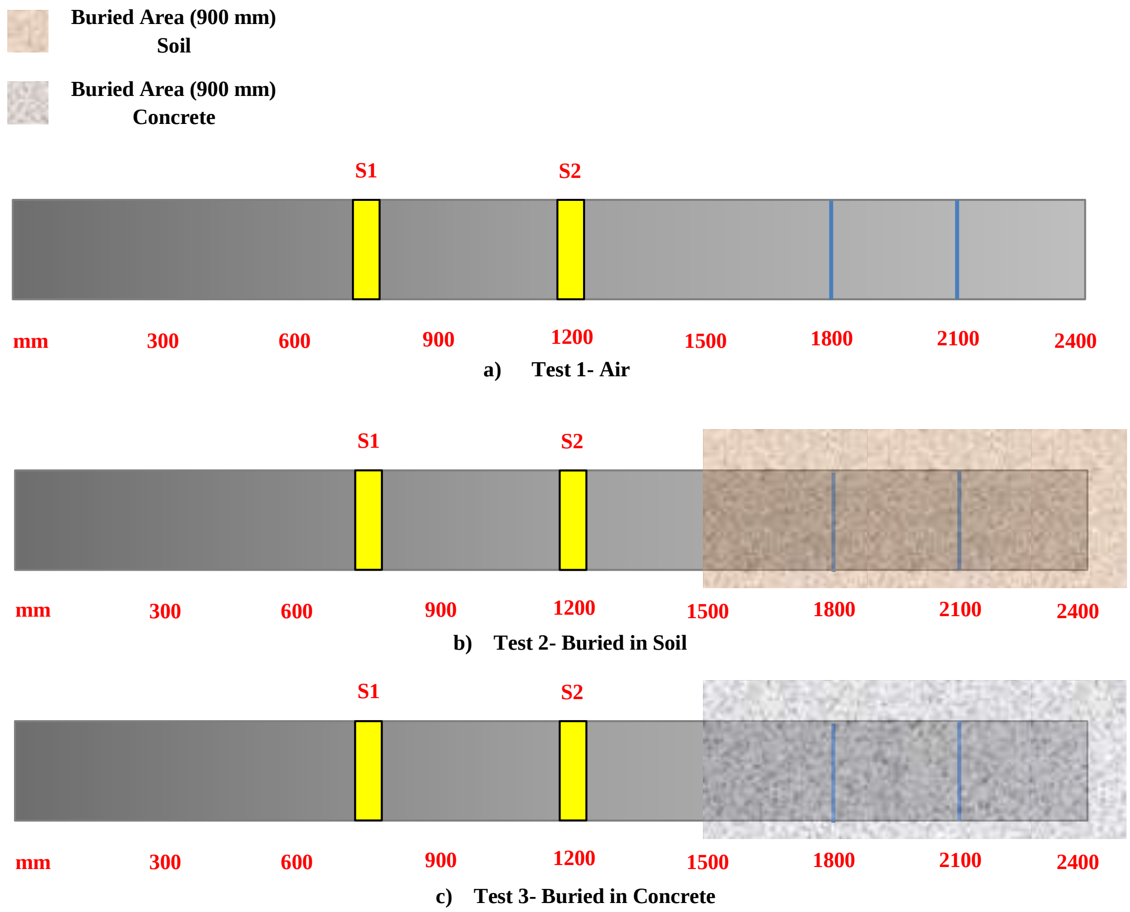


Figure 9. Lamp post mock-up un-buried

The data was collected with an Innerspec PowerBox H instrument along with the MRUT MS Scanner. The sensor works in PE configuration at an excitation frequency of 128 kHz, positioning the transducer on top of the magnetostrictive strip (S1 and S2).

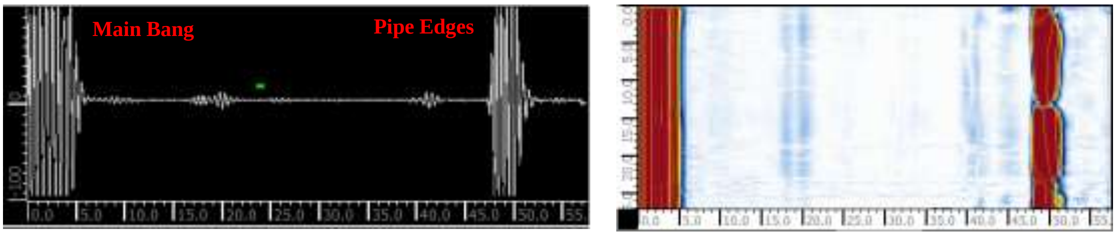
Figure 10. Lamp post inspection using Innerspec PowerBox H and MRUT MS Scanner (experimental trials)

The results from the trials are presented in the following sub-sections. The coil used to form the B-Scan images is non-focused with an aperture of 2 inches. The data is presented before and after applying the signal processing algorithm Synthetic Aperture Focusing Technique (SAFT) available in the PowerBox H.

All the data showcased in this manuscript was gathered at the same gain value (0 dB) so results from different experiments can be compared.

4.1 Air

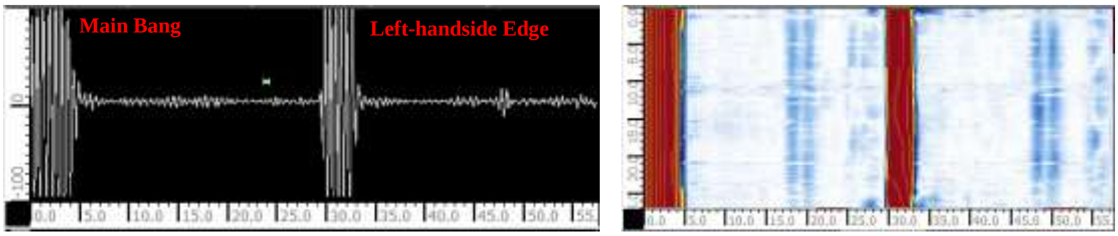
Initially the pipe was inspected before machining any defect and exposed to air. The B-Scan of a 360° inspection from test point S2 is shown in Figure 11b. One of the A-Scans that are part of the B-Scan is depicted in Figure 11a. The X-axis is expressed in inches whereas the Y-Axis represents the signal amplitude in percentage. The echo shown at about 47 inches (1200 mm) is the reflection caused by both pipe edges. As the strip is located in the middle of the pipe, the echoes coming from both edges are overlapped at 47 inches. The amplitude value in a defect-free area (gating the area between defects D1 and D2) is 0.4%.



a) b)

Figure 11. Pipe inspection exposed to air before machining the defects from test point S2 a) A-Scan, b) B-Scan

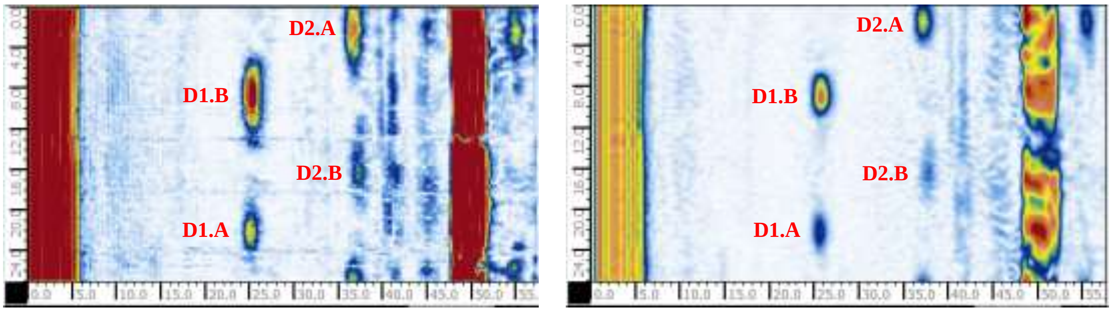
The A and B-Scans obtained when the inspection was performed at test point S1 are plotted in Figure 12. The echo shown in Figure 12a at about 28 inches represents the left-hand side pipe end. The amplitude value in a defect-free area is 0.49%. The right-hand side edge could be seen if the data window is increased (it will be seen in subsequent figures).



a) b)

Figure 12. Pipe inspection exposed to air before machining the defects from test point S1 a) A-Scan, b) B-Scan

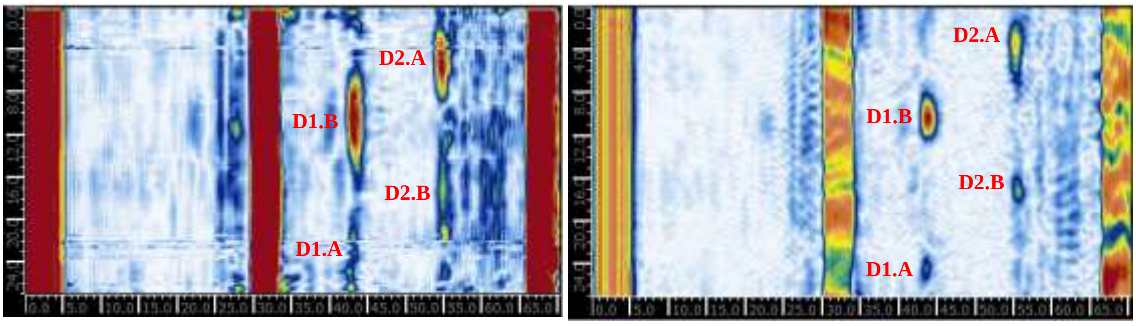
After machining the defects, new measurements were taken on the same test points. Reflections from the defects which are closer to strip S2 are depicted at 24” (600 mm) in Figure 13b. Reflections from the defects located farther to the strip appear at 35” (900 mm). In order to have a reference, the amplitude of the reflection coming from defect D1.B is 99.94% (measured in the raw data, Figure 13a).



a) b)

Figure 13. Pipe inspection exposed to air after machining the defects from test point S2, B-Scan a) Raw Data, b) After applying SAFT

The plots in Figure 14 show the inspection results from strip S1. The two reflections displayed at 28 inches (700 mm) and 67 inches (1700 mm) are representative of the left and right-hand side pipe edges respectively. Reflections from defects D1.A and D1.B appear at 44 inches (1100 mm) whereas the ones from D2.A and D2.B show at 55 inches (1400 mm), which matches with the information provided in Figure 8. In order to have a reference, the amplitude of the reflection coming from defect D1.B is 99.96% (measured in the raw data, Figure 14a).



a) b)

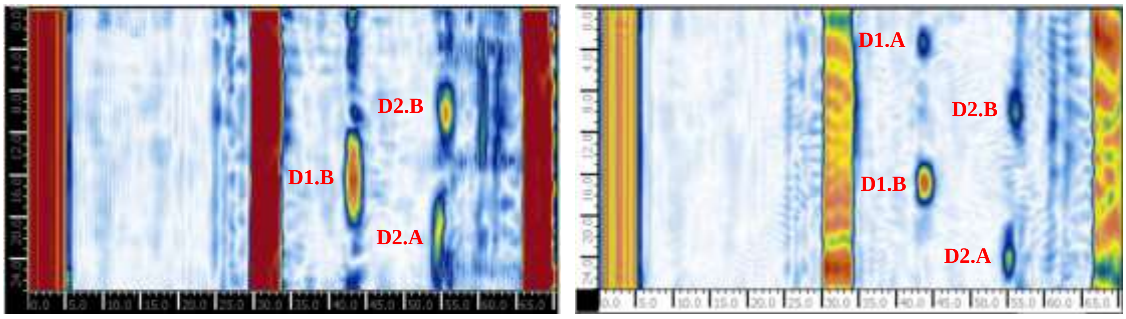
Figure 14. Pipe inspection exposed to air after machining the defects from test point S1, B-Scan a) Raw Data, b) After applying SAFT

In light of the results, the MS Scanner was able to easily identify the four flaws and properly determine the distance from the scanner to the defects. The visualization of the results in Figure 13b and Figure 14b is much clearer than in Figure 13a and Figure 14a (raw data) thanks to the application of the SAFT algorithm, which significantly increases the resolution and Signal to Noise Ratio (SNR).

The results shown in the following sub-sections correspond to the tests performed burying the pipe in soil and concrete partially. The propagation of guided waves in embedded waveguides is always accompanied with attenuation due to leakage of energy radiating out into the embedding material. The extent of leakage depends on the material properties of both the pipe and the embedding material [9].

4.2 Air-Soil Interface

In this section, the capabilities of the MRUT MS Scanner for detecting defects buried in soil are discussed. The inspection was carried out from the strip located farther from the machined defects (strip S1). Figure 15a shows reflections from defects D1.B, D2.A and D2.B that are related to the defects. There is a reflection in the area where D1.A should be, but the indication is not clear enough. After applying the SAFT algorithm (Figure 15b), the four defects are now clearly visible compared with the baseline values. The amplitude of the reflection coming from defect D1.B is 93.66%.

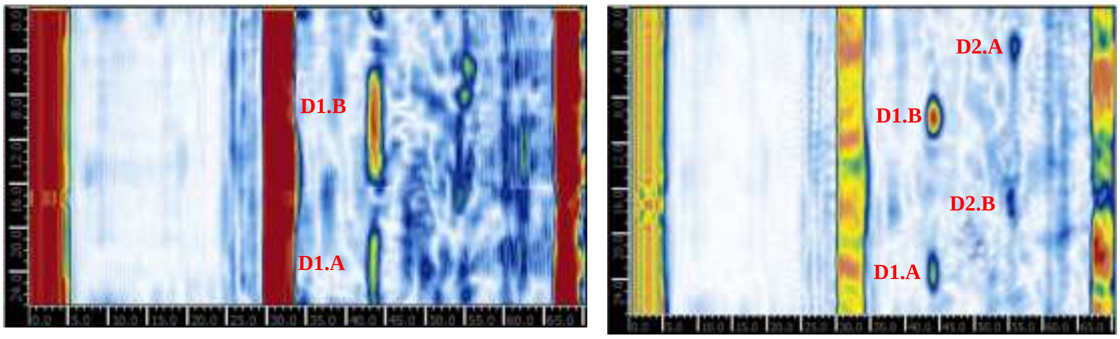


a) b)

Figure 15. Pipe inspection air-soil from test point S1, B-Scan a) Raw Data, b) After applying SAFT

4.3 Air-Concrete

In this section, the capabilities of the MRUT MS Scanner for detecting defects buried in concrete are discussed. The inspection was accomplished from the strip located farther from the machined defects (strip S1). Looking at the raw data depicted in Figure 16a, it is easy to identify the defects closer to the strip (D1.A and D1.B). Although there are reflections at the length where defects D2.A and D2.B are expected, they are not conclusive. After applying the SAFT algorithm (Figure 16b) all four machined defects become visible. In this case, the amplitude of defect D1.B is 86.34%.



a) b)

Figure 16. Pipe inspection air-concrete from test point S1, B-Scan a) Raw Data, b) After applying SAFT

In order to summarize the results presented in this section, the amplitude of the signal reflected by each defect has been quantified. In general, the amplitude of the reflected signal is higher when the pipe is exposed to air. Once buried, reflections from defects are attenuated due to leakage of energy radiating out into the embedding material. The reflected echoes seem to be more attenuated when the embedding material is concrete which makes sense taking into account its higher mass attenuation coefficient [10].

Table 3. Reflection levels on the three scenarios studied (Strip S1)

	Amplitude (%)			
	D1.A	**D1.B**	**D2.A**	**D2.B**
Air	39.02	99.96	90.38	40.52
Soil	48.78	93.66	18.22	39.84
Concrete	30.86	86.34	17.82	25.2

5. Conclusions

The capabilities of the MRUT MS Scanner for defect detection in buried areas, in conjunction with Innerspec PowerBox H instrument have been demonstrated, positing this technique as a great alternative for inspection of buried lamp posts and other inaccessible structures.

The MRUT MS Scanner technique permits inspection from 0.1m to 3m with far greater resolution and detection capabilities than Long-Range UT (LRUT), and it is applicable for pipes, tanks, and any structure where the magnetostrictive strip can be attached.

The MS Scanner, which makes use of the magnetostrictive effect for ultrasound generation, clearly detected the four different defects machined on the test samples even when buried in soil and concrete. The defects in the pipes had diameters ranging from 0.12 inches to 1 inch, and represented wall loss ranging from 30% to 75%. The MS Scanner was able to identify defects 1400 mm away from the probe on all buried pipes. In this regard, the SAFT algorithm available in the PowerBox H software was instrumental to have enough Signal-To-Noise and resolution.

The patented MRUT MS Scanner is the newest addition to Innerspec's MRUT toolkit, which offers the most complete selection of sensors and accessories for Medium-Range inspection in the market.

6. References

[1] NBC, NBC San Diego, 11 Septemeber 2015. [On-line]. Available: https://www.nbcsandiego.com/news/local/Dog-Urine-Contributes-lamp-post-corroded-downtown-san-diego-326839961.html.

[2] E. Du Trémolet de Lacheisserie, Magnetostriction, CRC Press, 1993.

[3] D. Jiles, Theory of magnetomechanical effect, J. Phys. D: Appl. Phys, vol. 28, pp. 1537-1546, 1995.

[4] Y. Young Kim y Y. Eui Kwon, Review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguides, Ultrasonics, nº 62, pp. 3-19, 2015.

[5] G. Wiedemann, Magnetische untersuchungen, Ann. Phys, nº 193, pp. 193-217, 1862.

[6] N. Tzannes, Joule and Wiedemann Effects - the simultaneous generation of longitudinal and torsionalstress pulses in magnetostrictive materials, IEEE Trans. Sonics ultrason., nº 13, pp. 33-41, 1966.

[7] R. Sass y M. Kidd, Detection of defects and Corrosion under pipe supports and innaccesible areas using EMAT Medium Range UT Techniques.

[8] S. Doctor, T. Hall y L. Reid, SAFT- the evolution of a signal processing technology for ultrasonic testing, NDT international, vol. 19, nº 3, pp. 163-167, 1986.

[9] E. Leinov, M. Lowe y P. Cawley, Investigation of guided wave propagation in pipes fully and partially embedded in concrete, The Journal of the Acoustical Society of America, nº 140, pp. 4528-4529, 2016.

[10] M.N. Alama, M.M.H. Miahb, M.I. Chowdhurya, M. Kamala, S. Ghosea, Runi Rahman, Attenuation coefficients of soils and some building materials of Bangladesh in the energy range 276–1332 keV, Applied Radiation and Isotopes, nº54, pp. 973-976, 2001.