Discrimination of top and bottom discontinuities with MFL and the Surface Topology Air-gap Reluctance System (STARS)

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Abstract

Discontinuities due to corrosion can occur on the top and bottom surface of above ground storage tank (AST) floors and can, if unknown increase the likelihood of a leak as inadequate repair strategies may be applied. Although surface discrimination can in some cases be achieved visually, low lighting conditions and in particular ASTs with opaque coatings on the top surface of the floor make the task of identifying top surface discontinuities difficult. This paper presents a novel approach to the problem of discriminating top and bottom discontinuities, an approach that has been incorporated into the next-generation of Floormap™ MFL scanner (Floormap3D™) developed and manufactured by Silverwing (UK) Ltd.

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1. Introduction

Magnetic flux leakage (MFL) inspection machines that are commonly used to ascertain the condition of the AST floor can detect corrosion which resides on both the top and bottom surface but in general is unable to distinguish between them. Rate and type of corrosion can significantly alter the life expectancy of an AST floor and is based on many factors including the site, design and foundation. According to Moss et al. [1], bottom side (or underfloor) corrosion "strikes randomly" in that "tanks badly affected may be situated next to tanks which are not affected" and is normally attributed by trapped water, aggressive ground salts or chemicals that can seep through the tank foundation from the surrounding environment. Top side (or internal) corrosion is normally found in the presence of sulphur reducing bacteria (a source of pinhole or 'pipe' type discontinuities) and is also attributed by contamination of the stored product [1]. A water layer, product deposits or sediments are often situated at the bottom of the tank and underneath the typical hydrocarbon product being stored. As a result, the floor of an AST usually exhibits the highest corrosion rate [2]. Additional environmental parameters such as elevated temperatures or a coastal location can accelerate the rate of both top and bottom side corrosion.

Liners or coatings applied to the top surface of the floor can extend the life of the AST and maintain purity of the stored product [3]. However, in terms of maintenance, the application of a coating can make inspection difficult as:

1. Coating can change the characteristics of the MFL signal due to extra lift-off from the surface of the specimen and
2. Coatings are normally opaque and so in many cases, distinguishing between top and bottom discontinuities, visually or otherwise becomes less trivial.

With or without an internal coating, it is highly recommended in [1] that to locate top-side corrosion, it is essential that the tank floor is thoroughly cleaned and while expensive, it has proven to be the only sure way of uncovering discontinuities. If visual inspection is possible, an inspector should provide surface discrimination information but this task can be time consuming. Attributes such as human error, fatigue, eye condition, limited lighting and time constraints are additional factors that can degrade the quality of top surface information.

Current approaches to identify top surface discontinuities include visual inspection and physical measurement. Such approaches are normally through manual measurement with a pit/profile gauge and may be accompanied with photographic recordings, making the process very time consuming. Profiling the surface through laser scanning is a possibility but measures on coated tanks would likely be difficult. Also, readily available eddy current technologies can be used to provide information about top side corrosion based on the depth of surface penetration, however this approach relies heavily on operator interpretation.

The main reason to address the top and bottom problem relates to improvements on the maintenance and repair strategies, cost of removing coatings for maintenance and to assist risk based analysis. In order to fully evaluate future corrosion rates in order to determine service intervals, both topside and underside corrosion needs to be evaluated so that in-service intervals can be further optimised [1]. This paper describes a novel and complementary approach to MFL in order to distinguish between discontinuities that reside on the top surface of a tank floor and to those that are on the bottom using a conventional magnetic yoke.

2. MFL with additional top/bottom discrimination

MFL for tank floor inspection was proposed in 1988 by Saunderson [4] as a means to inspect tank floors in a rapid manner. Along with the key benefit of inspection speed, MFL is extensively used for tank floor inspection due to its high probability of detecting discontinuities, the ability to inspect through coatings (up to 6 mm thick depending on the thickness of the parent material), its design as a non-contact tool and its ability to make the machines battery portable for ease of use and safety. In the context of storage tanks, very little work has been reported on the ability of MFL machines to distinguish top and bottom corrosion. Most related work to such discrimination are found in the context of pipeline inspection; a closely related application. There are two main approaches to ascertain the surface origin of a discontinuity, either through analysis of the recorded MFL signals or with complementary sensors.

Surface discrimination through analysis

The inability to discriminate between top surface and bottom surface corrosion is claimed by many as one of the major limitations associated with the use of the flux leakage approach [5–9]. The similarity of MFL signals coming from top and bottom discontinuities that are 70% deep and of equal geometry are demonstrated with two example signals is illustrated in Figure 1. These signals are generated using a 2D finite element model. The two signals demonstrate similar characteristics with only a noticeable difference coming from the different amplitudes. MFL signals from top surface discontinuities do tend to have slightly higher amplitude than the equivalent MFL signals coming from bottom surface discontinuities; the difference in amplitude is approximately 10%. Small variations in the depth of a discontinuity from one surface could result in an identical MFL signal that originate on the opposite surface; illustrating that discrimination of top and bottom discontinuities from MFL signals, in particular its amplitude is difficult.

Surface discrimination through complementary sensors

Complementary sensors to the conventional MFL do provide a solution to the problem of discrimination the surface origin of discontinuities. Two suggestions for complementary signals to the MFL approach were postulated by Charlton [7] in 1995. The first and most popular approach (with other surface discriminatory tank floor scanners) utilise the properties of eddy currents (EC) in particular the principle of the *skin effect*. By tuning properties that relate to the skin effect, the depth of eddy current penetration can be adjusted and in conjunction with traditional MFL sensors, the defects along with their surface origin can be ascertained. The second approach suggested, which no other reference or implementation can be found is to use "electostatic transducers sensitive to permittivity variations due to increased air-gap volumes in the presence of top surface defects" [7]. These complementary signals form the basis of the second approach that is employed in this work to generate the surface map of the top surface.

During the course of this research there has been no work found and no commercial machines available that is able to generate a top surface profile from variations within the air-gap. One possible reason for this is the dominant research in the field of pipelines; in particular the pipeline inspection gauges (PIGs) that rely heavily on the MFL approach. A major difference between the conventional PIG and tank floor scanner is the design of the magnetic yoke. An MFL PIG usually comprises of a yoke that is in contact with the internal walls of the pipe using highly permeable, flexible brushes; thus concept of 'air-gap' doesn't normally apply. One advantage of this approach includes a lower and more uniform reluctance path within the magnetizing circuit. The reason for this is that there is no variable air-gap and thus less influence from reluctance variations in the magnetic circuit and in-turn less noise on the amplitude of the MFL signal. In the context of tank floor inspection, many of the machines available, including a range of Floormap™

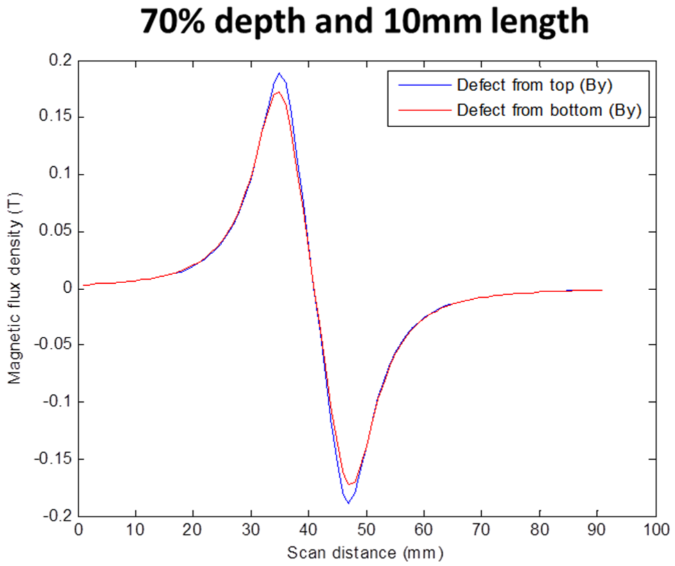

Figure 1: Two MFL signals, one generated from a top surface discontinuity and the other from an identical, albeit bottom surface discontinuity. Notice that the only discernible characteristic between the two signals is that top surface discontinuity is slightly higher in amplitude.

scanners (produced by Silverwing (UK) Ltd), are non-contact, meaning that an air-gap exists between the magnetic yoke and the inspection surface. The properties of an air-gap in a magnetic circuit will influence its overall reluctance. As the distance between the surface and the poles increase (i.e. increasing the air-gap) so does the overall reluctance of the magnetic circuit. Charlton [7] reported that the magnetic reluctance of the air-gap as a function of the lift-off gives a linear response. The air-gap and lift-off concept is the fundamental principle of top and bottom discrimination of the novel approach proposed here.

3. MFL and the air-gap reluctance measure

The basic principle of inspecting a ferrous specimen with MFL is to suitably saturate the local area of interest with a magnetic field. In the vicinity of a discontinuity, the reluctance to the induced magnetic field increases and if high enough, the induced magnetic field will diverge around the absence of material. This field can diverge around the discontinuity both within the surrounding material and also ‘leak’ outside its confides. This amount of leaking magnetic field is then measured by suitably placed magnetic sensors. To perform rapid inspection of an AST floor, a scanner with an array of sensors is normally used and all are arranged in a linear manner that is perpendicular to the direction of travel so that an area can be covered with one sweep.

The magnetic circuit is generated with the yoke arrangement shown in Figure 2 and comprises two magnets, a bridge, and two pole pieces. The magnetic yoke is situated in close proximity to the inspection surface at a height of approximately $4mm$. Traditionally, the lateral position of the magnetic sensors to capture the MFL is situated at an equidistant position between the two poles. The height of the MFL sensors from the surface of the specimen can act as an amplifier which increases the strength of the MFL signal when in closer proximity to the surface.

A simplified electrical analogue of the magnetic yoke is illustrated in Figure 3. From the electrical analogue, it can be seen that the equivalent magnetic reluctance of the yoke, both pole pieces and to an extent, the specimen on a uniform plate can be considered known parameters that are also fixed. In this simple analogy and by ignoring the plate specimen, the reluctance variations in the magnetic circuit can only be attributed to variations of the air-gap height. A larger air-gap increases its reluctance within the magnetic circuit and is equivalent to increasing the resistance of the air-gap in the electrical analogue. In the field, air-gap variations can be attributed by several factors including deformations such as rippling of the floor plates and discontinuities on the near/top surface of the specimen. In the

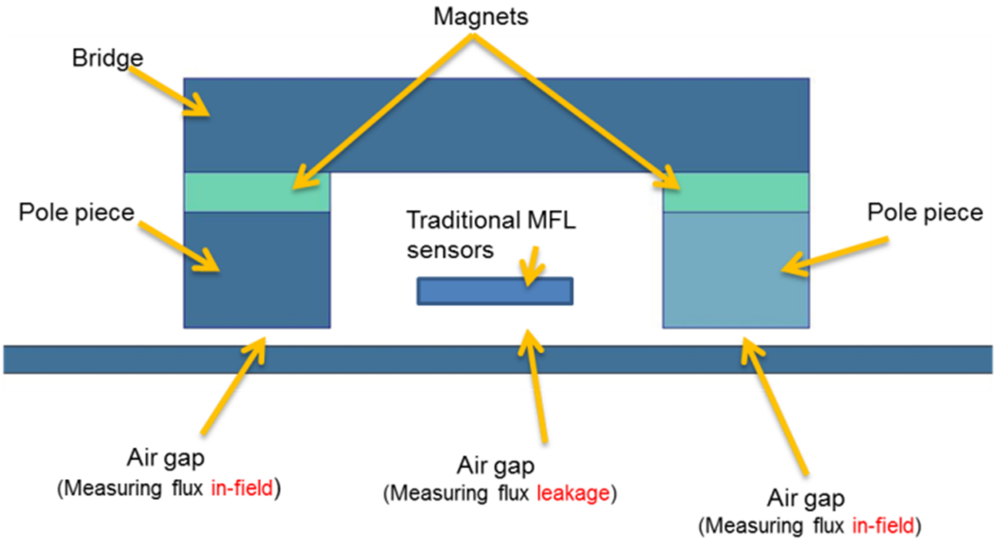

Figure 2: Components of the magnetic yoke and the location of traditional MFL sensors. Non-contact positions of the yoke and sensors are highlighted by the locations of the 'three' air-gaps.

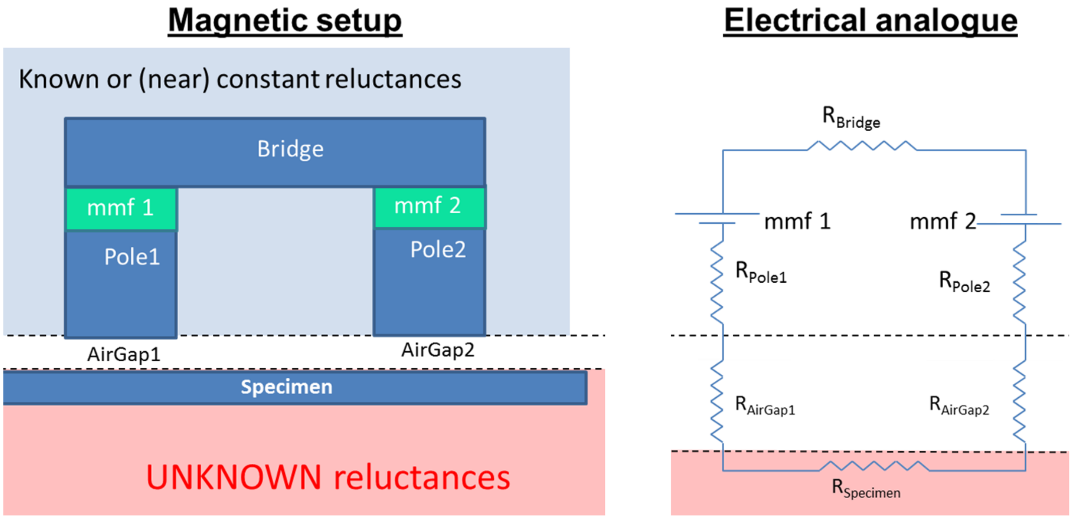

Figure 3: Magnetic circuit and an equivalent, yet simplified electrical analogue. Each of the magnetic components, including the air-gaps are represented by resistors of the electric circuit. The magnets are represented by voltage sources.

case of top surface discontinuities, changes in the distance between the bottom of the pole piece (either pole 1 or pole 2) would influence the air-gap in a near-linear fashion [7]. In the context of a discontinuity, an increased depth would increase the distance of the air-gap (i.e. the distance under the pole piece) and proportionally increase the reluctance of the air-gap. Thus, a measure of top surface discontinuities with appropriately situated sensors under the poles can be made.

Measures of air-gap variations are conducted with magnetic sensors (similar to the MFL sensors) that are able to

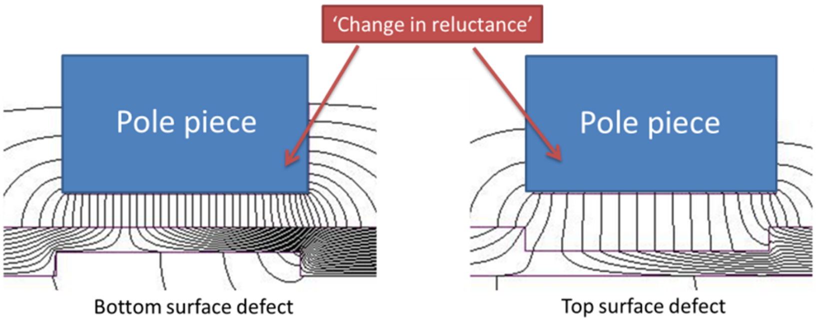

Figure 4: Distribution of the lines of magnetic flux under the pole piece of the magnet when a discontinuity is on top and when an equivalent discontinuity is on the bottom. Note that only one pole piece of the magnetic circuit is shown and the size of the discontinuity is chosen for illustration purposes. As the distance between the bottom surface of the pole piece and the surface of the specimen increases, the density of the lines of magnetic flux decreases and thus a change of reluctance which is then measured.

measure the variation of the magnetic flux density as a function air-gap distance; the quantity of lines on Figure 4 denote magnetic flux density variations from both a top and a bottom surface discontinuity; the air-gap distance is a function of the reluctance as other parameters such as the permeability within the air-gap can be considered constant. A brief formulation of the theory is now discussed.

The definition of magnetic reluctance can be expressed as:

$$\mathcal{R} = \frac{\mathcal{F}}{\Phi} \tag{1}$$

Where $\mathcal{F}$ is the magneto-motive force (MMF) and Φ is the magnetic flux in Webers. The reluctance of a magnetic field can also be calculated is given by:

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A} \tag{2}$$

Where l is the length of the air-gap portion of the circuit in meters, μ_0 is the permeability of free space, μ_r is the relative magnetic permeability of the material and A is the cross-sectional area of the circuit in meters squared. Consider that the permeability of the air-gap remains and that the cross-sectional area of the sensing element is constant, then the only variable is the length l, i.e. the distance or lift-off between the pole piece and the surface of the specimen. Therefore, as the length l varies, and the magneto-motive force remains constant, then the reluctance can be calculated from the magnetic flux. In the approach presented here, the density of the magnetic flux is measured and a relationship between the lift-off can be calculated when equations 1 and 2 are rearranged to the following:

$$\Phi = \frac{\mathcal{F} \mu_0 \mu_r A}{l} \tag{3}$$

With a suitable array of sensors under one or both poles of the magnetic yoke and other components known or normalised, the reluctance of the air-gap is then attributed by top surface discontinuities and can give a map including their severity.

The under-pole approach has been integrated into the new *Floormap3D*™ tank floor scanner manufactured by Silverwing (UK) Ltd to provide discriminatory information to conventional MFL signals. This novel and complementary technology to traditional MFL tank floor scanning has been developed by Silverwing (UK) Ltd and is termed the surface topology air-gap reluctance system (STARS). An example recording of data from both MFL and the STARS generated from corresponding defects that reside on the top and bottom of a mild steel plate are shown in Figure 5. Section (a) of Figure 5 illustrates the cross-section along the centre of the steel plate with defects of depths 20%, 40%, 60% and 80%, the first illustration are when these defects are on the bottom and one when the defects are on the top. These defects have semi-sphere profiles and have been machined using a ball-end cutting tool.

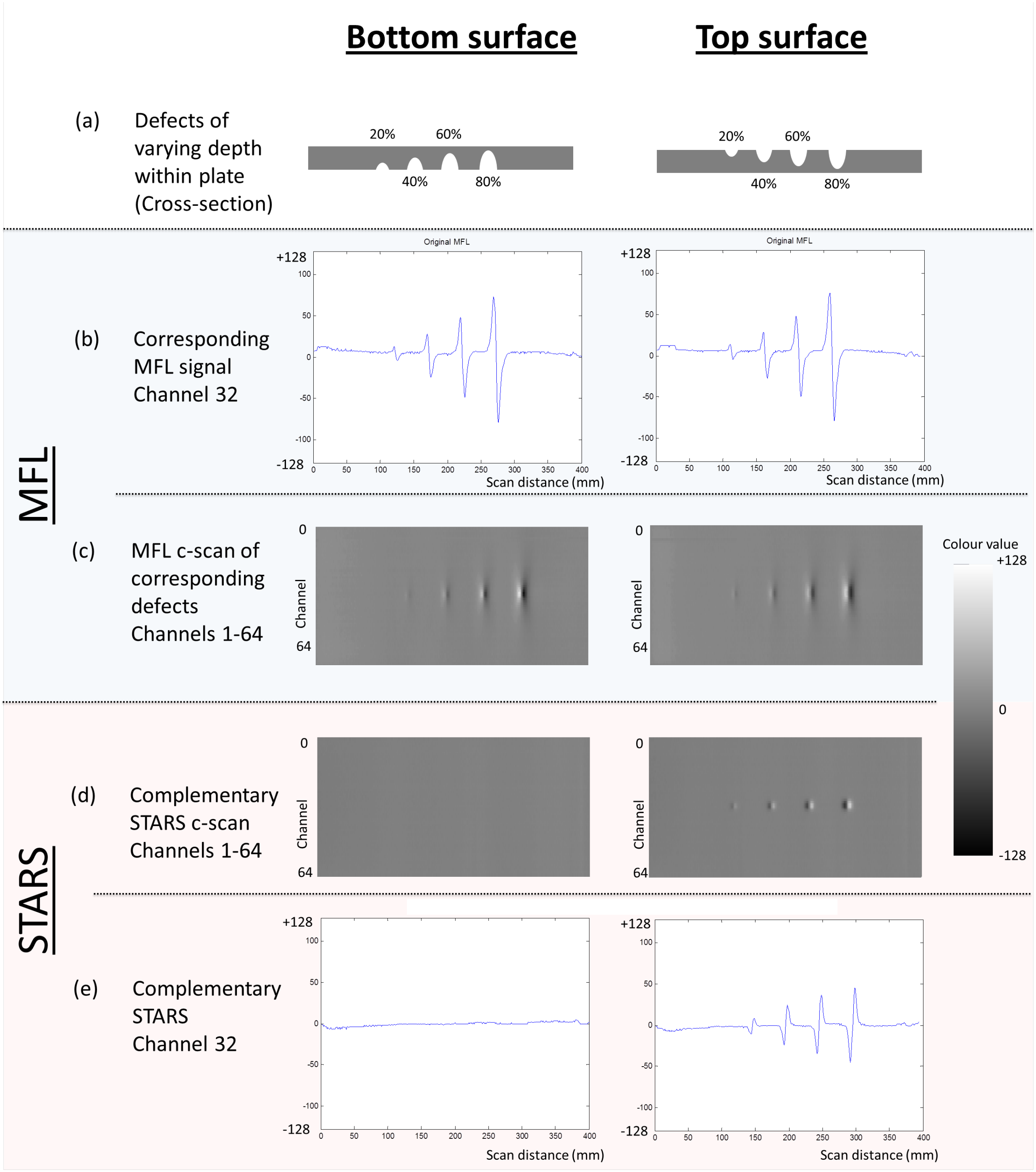

Figure 5: MFL signals and complementary STARS signals. A combination of both approaches can be used to discriminate the surface origin of discontinuities; those coming from the top and those from the bottom.

Section (b) and (c) illustrate recordings of a traditional MFL signal coming from the corresponding defects. (b) in Figure 5 illustrates a bipolar MFL signal coming a single magnetic sensor travelling along the top surface of the plate at a height of 3*mm*. As discussed earlier, the MFL signals have similar characteristics between discontinuities from the top and those with equivalent geometries on the bottom. However, a small increase in amplitude attributed by top surface discontinuities; a characteristic that is unreliable to determine the surface origin of a defect. (c) provides a c-scan/plan view of the defects where the intensity of the bipolar MFL signal corresponds to the 'colour value' scale and that the colour grey represents zero. The sensor or channel number coming from a linear array of 64 sensors is present on the ordinate. The scan position is presented on the abscissa as the array of magnetic sensors travels along the surface. As the defect becomes deeper, the intensity of the MFL signal increases proportionally. This is not directly proportional to the depth but more closely related to the volume, as reported by the early work of Saunderson [4]. The volume increases in a proportional manner with depth when a ball-end cutter is used to create these defects and is the reason why these defect signal appear to increase in a near-linear fashion. As reported by Atherton and Daly [10], the MFL signal extends or 'bleeds out' across the channels, while the length of the defect (along the scan distance) relates to the positive and negative peaks of the MFL signal. This makes sizing the defect less trivial as the width of the defect is less representative.

Diagrams (d) and (e) illustrates the information coming from the complementary STARS sensors that are situated under the pole piece. The first diagram in section (d) represents a c-scan type image coming from a linear array of 64 STARS sensors when defects reside on the bottom surface. In this instance, there is no indication of defects being present. However, when defects are on the top surface, the STARS sensors provide a proportional indication of the defect loss. In both (d) and (e), the STARS signals demonstrate that only top surface discontinuities are recorded and so in conjunction with traditional MFL signals from (b) and (c) that measure the severity of corrosion from either top or bottom, the surface origin can be ascertained. Another advantage of being able to discriminate between top and bottom discontinuities is the ability to adjust the MFL signals to compensate for slight differences in the amplitude as illustrated by the example MFL signals in Figure 1.

4. Conclusion

This paper presents a novel approach to discriminate top and bottom surface discontinuities when used in conjunction with MFL whilst maintaining all its other advantages including inspection speed, probability of detection and ease of interpretation. The new approach involves complementary sensors installed into the air-gap of the magnetic circuit used in traditional MFL tools. Measuring the reluctance changes of the air-gap, attributed by top surface variations can be used to discriminate top and bottom defects recorded with the MFL approach. Patents for the STARS approach described here are pending in both the EU (EU: GB1105193.5, GB1110889.1, GB1109371.3) and USA (US: 13175440).

References

[1] C. J. Moss, R. R. Griffiths, A. Bishop, and M. Dinon, "Life management of above ground atmospheric storage tanks," *10th APCNDT Brisbane*, 2001.

[2] P. E. Myers, "Aboveground storage tanks." *McGraw-Hill*, 1997.

[3] H. Buisman, "Getting to the root of leak problems." *Tank storage*, pp. 50–51, September 2006.

[4] D. H. Saunderson, "The mfe tank floor scanner - a case history." *IEE colloquium on non-destructive evaluation*, 1988.

[5] D. L. Atherton and M. G. Daly, "Finite element calculation of magnetic flux leakage detector signals." *NDT international*, 1987.

[6] Z. You, R. A. Brooks, R. Colman, and P. Bebick, "Apparatus for discriminating defects in top and bottom surfaces of objects." *U.S. Patent: 5473247*, December 1995.

[7] P. C. Charlton, "A theoretical and experimental study of the magnetic flux leakage method for the analysis of corrosion defects in carbon steel plate." *PhD Thesis, Swansea institute of higher education*, 1995.

[8] S. Lukyanets, A. Snarskii, M. Shamonin, and V. Bakaev, "Calculation of magnetic leakage field from a surface defect in a linear ferromagnetic material: an analytical approach." *NDT & E International*, vol. 36, 2003.

[9] J. Wilson, M. Kaba, G. Y. Tian, and S. Licciardi, "Feature extraction and integration for the quantification of PMFL data," *Nondestructive Testing And Evaluation*, vol. 25, pp. 101–109, June 2010.

[10] D. L. Atherton and M. G. Daly, "Finite element calculation of magnetic flux leakage detector signals." *NDT International*, vol. 20 (4), August 1987.