Capability of modern tank floor scanning with Magnetic Flux Leakage

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Abstract. This paper focuses on state-of-the-art Magnetic Flux Leakage (MFL) technology for the inspection of storage tank floors. The primary advantage of the MFL approach is the ability to locate and estimate the size of defects over large areas in a quick and efficient manner. As with any inspection approach, there are limitations which can influence the consistency and reliability of reported defects. However, MFL sometimes appears to be considered as a simple technology screening approach where any competent inspector can interoperate their signals. However, there are misconceptions of the approach that might simply be due to a lack of awareness. Some perceived limitations will be outlined together with suggestions to reduce their effects. To assist with overcoming these parameters further, technological advancements such as a combination of high-resolution scanners and a complementary approach to top and bottom defect discrimination and lead more consistent and reliable inspections.

Keywords:
Magnetic flux leakage (MFL), Top and bottom discrimination, AST floor inspection

Introduction

The magnetic flux leakage (MFL) approach is extensively used for the non-destructive testing (NDT) of large steel structures such as aboveground storage tank (ASTs). MFL testing is well suited to the inspection AST floors due to its ability to cover vast areas quickly. These areas can be hundreds of m^2, requiring the MFL tool to find and ideally determine the size of any material loss with diameters in the region of *mm*'s. This means that MFL equipment must be able to provide *mm* positional accuracy and report severity of material loss for defects. However, it is the accuracy, repeatability and reliability of MFL signals for defect sizing that appears to be a common concern of the MFL community.

An NDT inspection of an AST can involve many different techniques but MFL is used to cover the vast majority of the floor surface area. The limitation of the coverage of such tools is down to their design and in the case of MFL, the limitation is normally the size of the magnetic yoke. Inspection quality is variable and is dependent upon correct setup, understanding the environment to be inspected and the level of knowledge the operator has about the technology. UT is a particular case where there exist various levels of education and qualifications. It appears that MFL has less attention and it can be argued that a number of perceived limitations with approach can be reduced through education and aided further with suitable training courses, whilst other limitations can be achieved through technology.

This paper aims to identify some basic concerns of the MFL approach and suggests means to address them through education to aid the quality of inspection and the technology to gather and analyse the vast quantities of data that can be gathered from modern MFL scanners.

1. Principal of MFL

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 defect or flaw, the reluctance to the induced magnetic field increases and if high enough, the magnetic field will diverge around the absence of material. This field can circumvent the defect within the surrounding material and also 'leak' outside its confides. The amount of leaking magnetic field can be measured by suitably placed magnetic sensors which are normally located near the surface. To perform rapid inspection of an AST floor, a scanner with an array of sensors is normally used and arranged in a linear manner that is perpendicular to the direction of travel so that an area can be covered with one sweep, mapping the material loss.

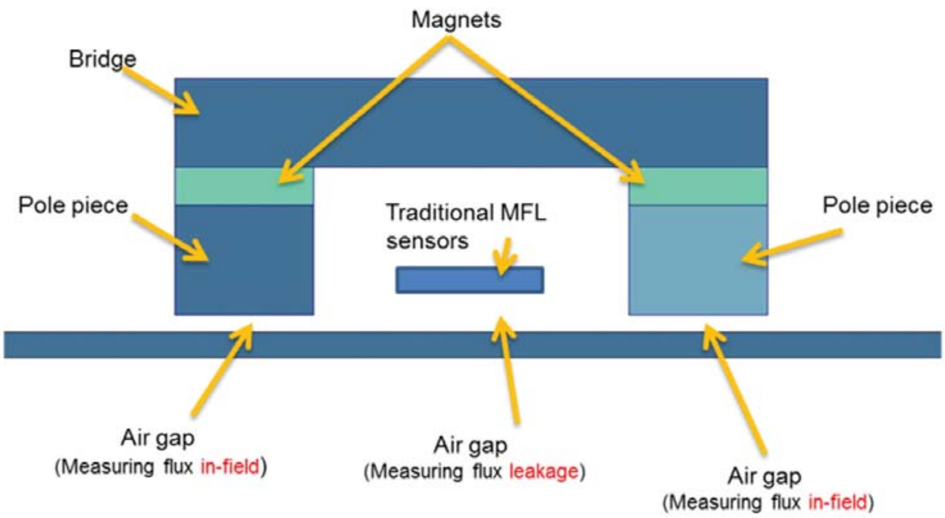

Fig. 1. Components of the magnetic yoke and the location of traditional MFL sensors. Non-contact positions of the yoke and sensors are highlighted by the locations of the 'three' air-gaps.

The magnetic circuit is generated with the yoke arrangement shown in Figure 1. 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 4 *mm*. 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 be used to amplify the MFL signal when in closer proximity to the surface.

2. Perceived limitations of MFL

In recent years MFL based technology has rapidly evolved and significant improvements to the capabilities of MFL based inspection equipment are becoming available, for example, the Silverwing Floormap3DiM [1]. However, even MFL's general capabilities, and the factors that affect its capabilities, remain confused or misunderstood; understandably resulting in confidence issues surrounding the MFL method. If a technique, the technology or its inherent limitations are appreciated then confidence can be increased. In this section we investigate some of the major factors that can give rise to MFL misconceptions.

2.1 MFL Competency

Though it may be apparent, a fundamental limitation is that current standards in MFL operation fall far below those expected in other inspection techniques such as UT. MFL is perhaps seen as a niche inspection technology and also perceived to be simple in comparison to other NDT methods such as UT. Even MFL operators themselves appear to suffer different perceptions and expectations of the technique, perhaps due to the limited number of training courses and material available with little focusing on its application, particularly in the context of tank floors. It is therefore understandable that the technique suffers from confidence issues and quite rightly the question arises: *what are the capabilities and limitations of MFL and in which inspection situations should it be applied?* With suitable education and experience, a knowledgeable operator will be able to confidently account for in-situ variability, interpret inspection data and culminate in a detailed report that can lead to efficient maintenance strategies and ultimately a prolonged in-life tank use. One way to achieve this level of competence, the recently established **SNT TC-1a** course [2], validated by the British Institute of Non-Destructive Testing (BINDT). This 80 hour course combines two levels of training and examinations which cover the general theory of MFL, the specific theory of controlling codes and specifications and practical application using modern MFL equipment, specifically targeting the floor of ASTs. The availability of such a course can help reduce the uncertainties associated with MFL and also provide the operator and inspector with advanced knowledge on defect interpretation.

2.2 Origins of uncertainty

MFL signals are considered simplistic when compared with other NDT methods such as UT and are perhaps perceived to require less operator interpretation. However, there is much information present in the MFL signal, beyond the simple amplitude, including the phase of the signal that can, for example, help determine if a signal has come from a weldment (i.e. a protrusion from the surface) or a defect.

A dense array of sensors can provide further information by helping to better estimate the shape of a defect, in particular its surface geometry. Enhanced technology and MFL knowledge can lead to the identification and classification of spurious indications from changing magnet/sensor lift-off from non-uniform coatings or false indications from poorly cleaned and prepared surfaces.

Whilst detection via MFL is relatively robust, interpreting defect sizing requires skill and experience; contrary to current belief MFL does require careful setting up, in terms of calibration, and its use. It is perceived that simply driving an MFL scanner without considering environmental parameters such as surface condition, plate and coating thickness and also general cleanliness of the tank floor will not effect the resulting MFL signals, but this is not the case. Without considering such factors, a signals interpretation can result in errors, just as with other NDT methods.

Though there are other forms of considerations in MFL that must be tuned to the application such as saturation, there are two key defect parameters that is needed for interpretation. The first is the ability to determine defect geometry and the second relates to knowledge of their surface origin. The next section considers these parameters through technological solutions to aid MFL signal interpretation.

3. Modern MFL capabilities

In this section two key advancements of AST floor inspection with MFL are presented. The first concerns the resolution of the sensors and its impact on defect shape analysis. The second advancement provides top and bottom discrimination of MFL signals using a complementary array of sensors.

3.1 Resolution

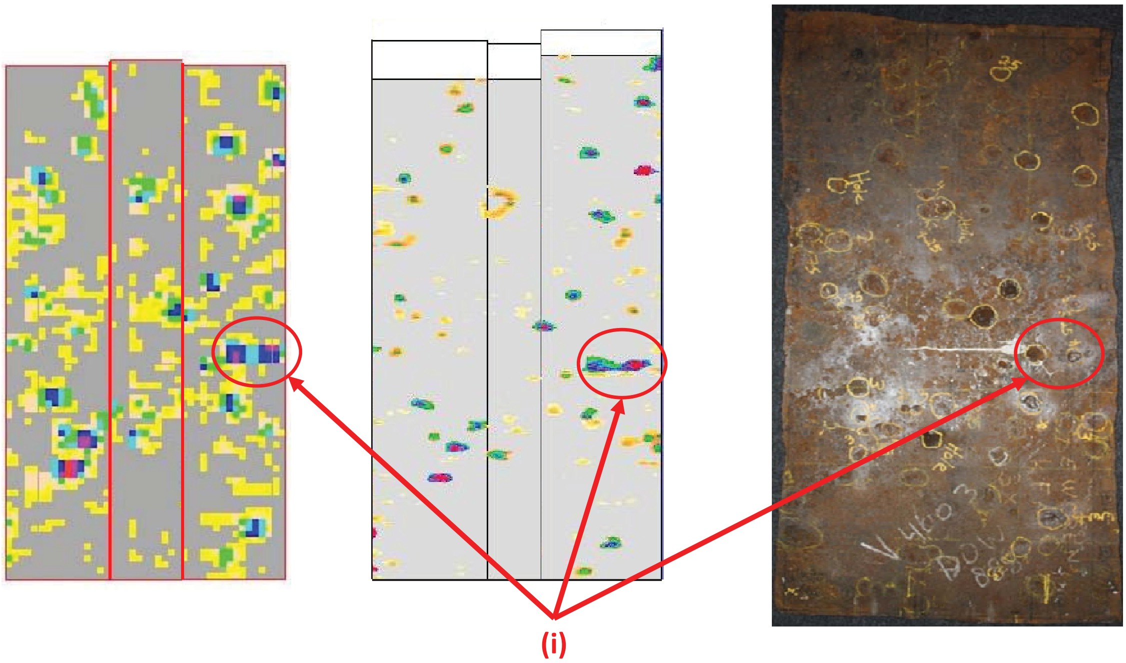

Fig. 2. Two MFL inspections of a real tank floor sample. Scans collected from the FloormapVS2i presented on the left and those from the Floormap3DiM shown in the centre. An image of the plate is shown on the right. The merged MFL signals from two separate holes and the corresponding defect locations on the plate is indicated by (i).

In Figure 2., an example of MFL maps from two different sensor densities. Each image comes from the same steel plate and is created from three scans. These are then stitched together to form a view of a plate. Based on either image, it is clear that there is a significant number of areas with material loss. Signals from the FloormapVS2i is presented on the left with those from the latest generation Floormap3DiM on the right. The defect map from the FloormapVS2i is generated from an array of sensors with 16 channels. This equates to a resolution of approximately 15 *mm* by 15 *mm*. Each measurement is represented by a square block and is colour coded based on the strength of MFL; low values of MFL are represented by yellow and green while higher levels of leakage are represented by blue and pink with maximum material in red.

The corrosion map coming from the Floormap3DiM can be seen to have defects with clear separations. With a sensor separation of around 4.5 *mm*, sampled at every 2 *mm*, the 3DiM represents a presented resolution increase by of a factor of 22.5 meaning that the likelihood of finding smaller defects increases. A further consequence of an increased resolution is the presentation of the defect shape, unlike their low resolution counterparts from the VS2i. It is also clear in Figure 2. that the increased resolution can help to segregate individual defects. However, there are certain conditions when defects or holes in close proximity generate such a high levels of leakage, that the resulting MFL signal appears to be merged to form one defect. Such merged signals are present, regardless of the density of the magnetic sensors and is thus perceived to be a consequence of induced magnetic field itself. An example of a merged MFL indication from two separate defects is indicated by (i). Though this can be seen as a limitation to MFL, the majority of the defects can be clearly correlated in the image of the real plate, well beyond the map presented with the VS2i.

3.2 Top and bottom discrimination

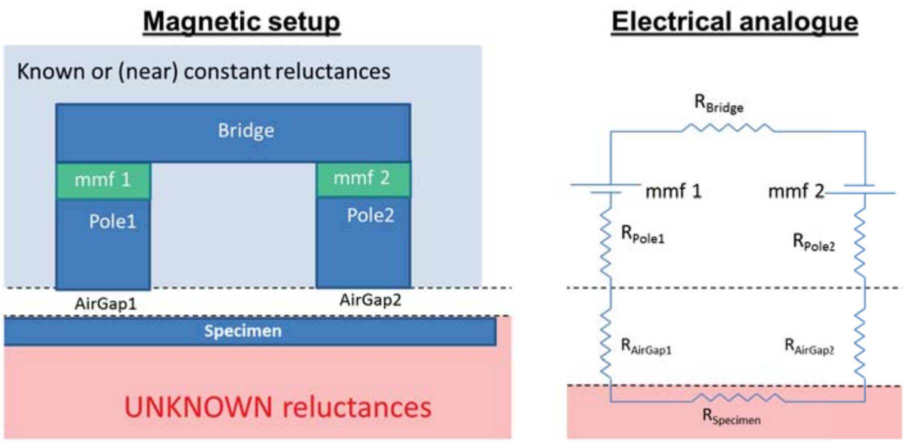

Fig. 3. A simple representation of components of a magnetic yoke and its corresponding electrical analogue.

The magnetic yoke shown earlier in Figure 1. is again illustrated in Figure 3. along with its electrical analogue. This is used to describe the approach to perform top and bottom defect discrimination. 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 constant parameters. Note that the two magnets $mmf1$ and $mmf2$ are represented by voltage sources in the equivalent electrical analogue. In this simple analogy, and by ignoring potential defect variations in the plate specimen, the only remaining reluctance variations in the magnetic circuit are the consequence of variations to the air-gap. In the presence of a larger air-gap, the magnetic reluctance would increase. This 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 defects on the top surface of the specimen. In the case of top surface defects, 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 [3]. In the context of a defect, 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 defects with appropriately situated sensors under the poles can be made.

Measures of air-gap variations are conducted with magnetic sensors (as used to measure MFL) that are able to measure the variation of the magnetic flux density as a function air-gap

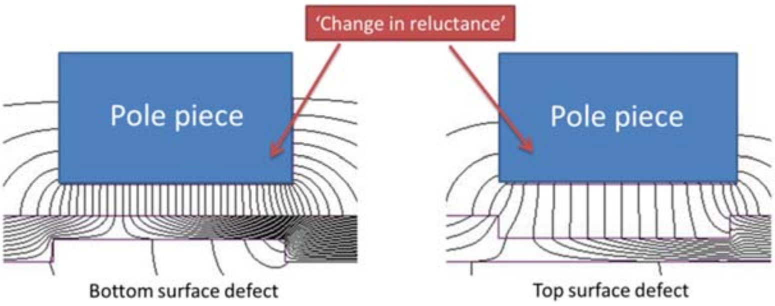

Fig. 4. Distribution of the lines of magnetic flux under the pole piece of the magnet when a defect is on top and when an equivalent defect is on the bottom. Note that only one pole piece of the magnetic circuit is shown and the size of the defect is chosen for illustration purposes. As the distance 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.

distance; the quantity of lines on Figure 4. denote magnetic flux density variations from both a top and a bottom surface defect; 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.

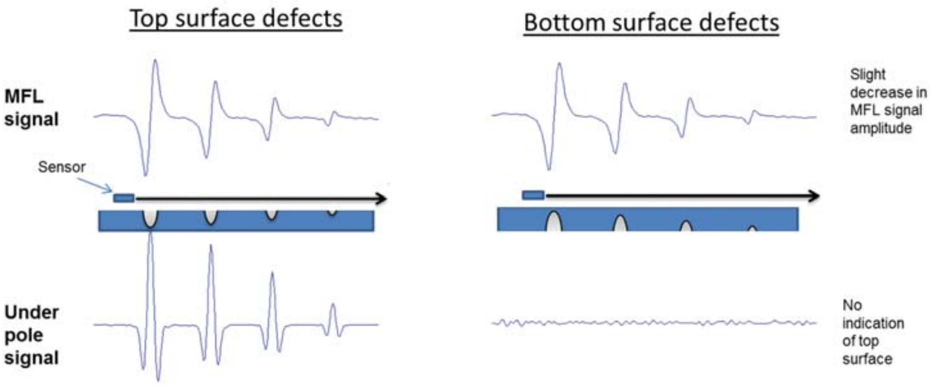

Fig. 5. MFL and corresponding START signals from separate top and bottom surface defects.

The under-pole approach has been integrated into the Floormap3DiM tank floor scanner and is able to provide discriminatory information when analysed in conjunction with conventional MFL signals. This complementary technology to traditional MFL tank floor scanning has been designed and developed by Silverwing (UK) Ltd and termed the surface topology air-gap reluctance system (STARS). An example recording of data from both MFL and the STARS coming from defects that reside on the top and bottom of a mild steel plate are shown in Figure 5.. The top-left 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 the illustration on the right shows defects and their corresponding MFL signals when the defects are on the top. These defects have semi-sphere profiles and have been machined using a ball-end cutting tool. Traditional bipolar MFL signals are shown on the top of Figure 5. from a single magnetic sensor travelling along the top surface of the plate at a height of $4.1mm$. As the defect becomes deeper, the intensity of the MFL signal increases in a proportional manner. Though this is not directly proportional to the depth but more closely related to the volume, as reported by the early work of Saunderson [4]. As mentioned in several publications [5, 6, 3, 7, 8], the MFL signals have similar characteristics between defects from the top and those with equivalent geometries on the bottom. Though there is a general yet small increase in amplitude attributed by top surface defects; this characteristic is deemed unreliable for discrimination. So the STARS approach is employed to perform measurements of only top surface defects. With knowledge of both top and bottom surface defects from MFL, the STARS can identify which surface those MFL signals originate.

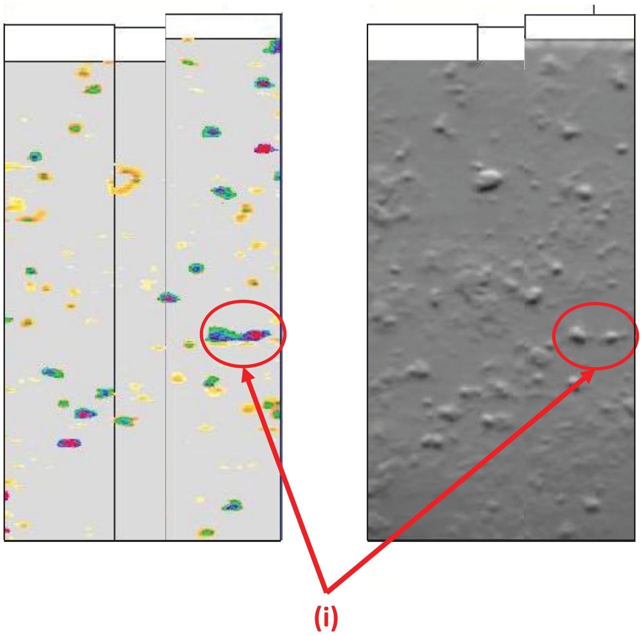

Fig. 6. MFL and corresponding STARS (top surface) maps from tank floor sample shown in Figure 2.. There is a clearer representation of the top surface profiles from the STARS measurements over those from MFL.

Figure 6. demonstrates the typical plan views that can be obtained with STARS. The MFL map is shown on the left and the STARS on the right and both have been recorded from the same sample plate shown in Figure 2.. Ignoring the colour palette, there is a clear difference in definition between the two maps. MFL signals presented have been rectified to show intensity, however, the bipolar nature of the STARS and the clarity of the defects provides clear indications with a grey-scale colour scheme. This gives the appearance of a 'moonscape' where the gradients of the bipolar signal can show the black or white edges of the defects. Being bipolar, the median of the signal which indicates no top surface indications is coloured grey. Note that the same sensor resolution has been used for both MFL and STARS but it is clear that STARS provides a greater distinction of the defect shape. MFL tends to merge defects that emit large leakage and are in close proximity, yet the equivalent STARS signals show clear and distinct defects. The clear distinction of the two merged defects described in section 2. is highlighted by (i). The majority of defects for this example plate lay on the top surface and only the through holes would be seen by STARS if the scan were performed on the bottom.

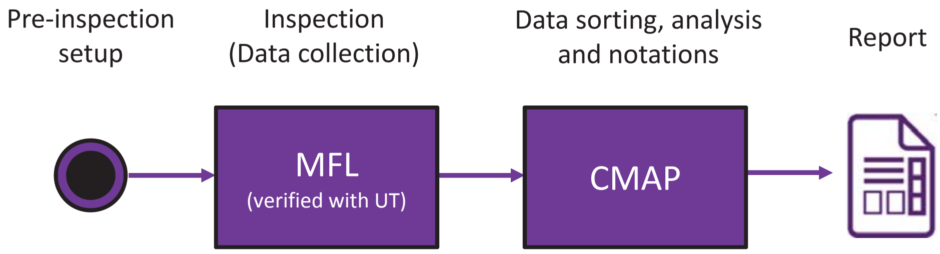

Fig. 7. Generalised inspection procedure from pre-inspection through to report.

4. Reporting

A general inspection procedure comprises of many stages. At the high level, this can be broken down into four parts, the pre-inspection setup stage, the inspection itself, the organisation, sorting and analysis stage which culminates in a report. Before the inspection takes place, the maintenance requirements are normally determined through appropriate standards, e.g. API [9] or EEMUA [10] for tank floors. Asset work history and previous inspection reports or data, if available, can be collected together to define the work procedure. Once the asset has been emptied and cleaned, a workforce can then perform the inspection. As mentioned in section 2., to obtain reliable data, it is crucial for the operators of the equipment to be trained to interoperate spurious signals, locate and report areas of the inspection that may lead to errors and the regions where the inspection tool cannot physical be scanned, i.e. the dead zones. In this instance, another form of inspection may be required to ensure that the whole tank floor is inspected. All such limitations should be either overcome with some complementary inspection or, at the very least, be recorded for the inspection report.

Currently report generation is a time consuming and laborious process that is normally performed after an inspection is complete when all the data is acquired. However, it is possible to build the report during the inspection to reduce the overall inspection time and also provide the asset owner with regular updates. Regardless, the amount of MFL readings obtained from the inspection of a single AST floor can result a large collection of data, gigabytes in size that needs analysis. One approach to gather the collected data in a presentable manner for the report is to manually append images of the scans in an effort to create a macro view of the entire floor. Without considering analysis, stitching the data together in a word processing package or extracting measurement for entry into a spreadsheet will likely be a time consuming task.

To improve the efficiency of analysis and reporting, data management tools to collect, present and generate reports are becoming more prevalent in inspection. For example, the 'CMAP' reporting tool created by Silverwing that can import MFL data and automatically generate a high-level visual representation. Defect shapes can be analysed at the micro view, while the tanks general condition can be viewed at the high-level. An example tank view with the typical levels of detail available is shown in Figure 8.

In addition to the analysis of each defect, the overall view of defects over the tank can offer additional high-level information as to its condition. For example, the pattern of corrosion may only be noticed on one half of the tank floor which could indicate a level of water ingress between the tank floor and foundation. Such an example is presented in Figure 8. where there is a concentration of indications on the top-left and bottom-right quarters of the tank.

Markers and annotations can be added to the data in CMAP to highlighted the aforementioned areas of concern or inspection data from other inspections can be added to cover the

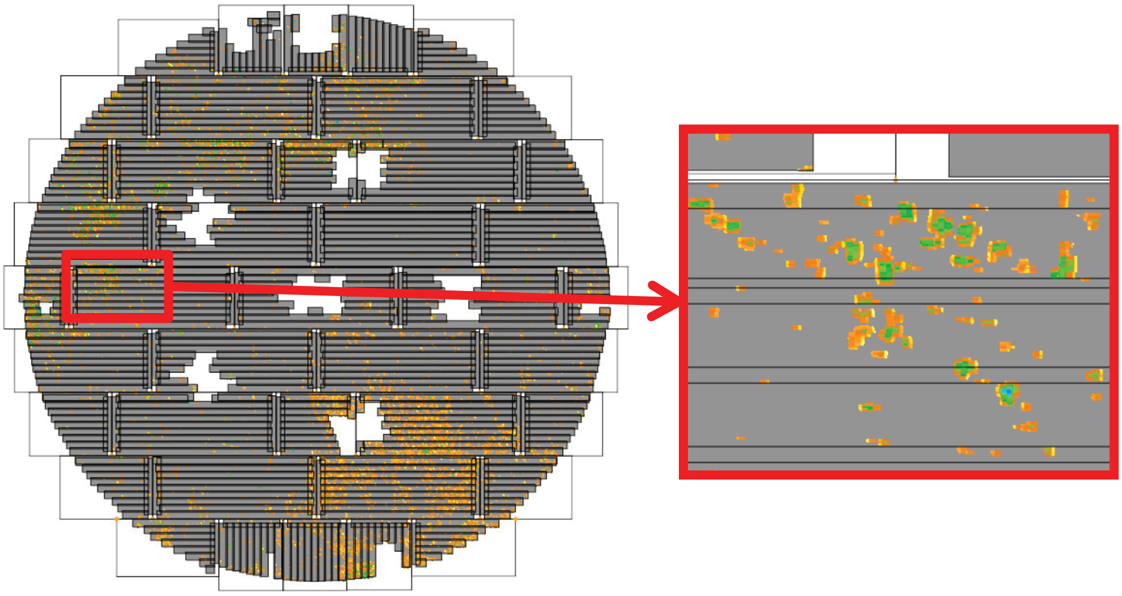

Fig. 8. Overall tank view showing the general trend of indications located by MFL. Notice that there is a concentration of indications on the top-left and bottom-right quarters of the tank. Such patterns can identify regions of the tank that maybe susceptible to, for example, external environmental conditions. A magnified section is also shown to demonstrate the level of detail that can be presented.

areas where the MFL tool was unable to access. After annotation, a report can be automatically generated on a customised company template.

From existing CMAP users, it has been found that such a reporting tool can reduce the time taken, from importing the data through to generating the final report by around 80%; a significant gain in reporting efficiency. An extensive review of CMAP and its capability to handle vast quantities of UT data is presented in an earlier publication [11]. Though focusing on UT in that paper, the data import and analysis process applies in principle to the data collected via MFL.

5. Conclusion

This paper has postulated reasoning towards the current lack of understanding that surrounds the MFL technique and the underlying technology. General misunderstandings of the approach has led to a lack of confidence because the perceived limiting factors have been wrongfully attributed to the technique. Though, most limitations are in fact due to a lack knowledge or competency. Through courses tailored to MFL and tank floor inspection, operators and inspectors can be educated to understand the capabilities of MFL and analyse such signals with confidence. However such education will only become widely utilised when asset owners demand competencies from inspection companies on the equipment used and techniques employed.

A secondary aim of this paper was to show how some perceived limitations have been overcome with technology. The MFL technique, with respect to understanding the theory and its application is advancing its capability and reducing its limitations. The solutions to these problems assist with analysis, improve the quality of data collected and intuitive analysis tools provides to the end user a comprehensive report. However if the technique and its true limitations and capabilities are not understood then the technique will stagnate, possibly mislead and continue to suffer from the confidence issues that seem to accompany it.

With vast quantities of data now being made available from high resolution scanners such as the Floormap3DiM, the efficiency of analysis and data interoperation also needs addressed. With automated stitching tools and advanced reporting capabilities, tools such as the CMAP software provides an efficient means of data management, analysis and reporting of the condition of a tank floor. To conclude, the MFL method for the NDT inspection of AST appears to have a bright future if the approach is understood and the technology advanced towards its full potential.

6. Acknowledgements

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