Solving inverse problems in magnetic field leakage sensor array inspection of petroleum tank floor

Resolvendo problemas inversos em campo magnético vazamento sensor array inspeção do chão do tanque de petróleo

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ABSTRACT
The MFL method is a qualitative inspection tool and is a reliable, fast, and economical nondestructive testing method for tank floors. In this paper, before presenting the defect reconstruction procedure, we studied the effect of defect parameters on the magnetic field leakage measured by a single Hall sensor. As predicted, the study of each parameter has demonstrated that any variation in the geometrical parameters of the studied defect induce a significant influence on the MFL signal amplitude and distribution; for this reason, all the defect parameters must be determined precisely and prudently. After that, we have studied the performance of defect shape reconstruction from MFL array sensor imaging and depth estimation while using an iterative inversion method. Indeed, the first stage consists of determining the defect width and length from magnetic flux leakage mapping reconstructed from the recorded signals of the micro-integrated magnetic sensors. As a second step, after coupling Comsol and Matlab software, the defect depth is obtained by coupling the 3D finite elements method and a fast iterative algorithm recently developed. Consequently, the defect shape and size are obtained after a few iterations with a relative error of less than 2%; which makes this method very appropriate for real-time defect reconstruction and quantification. Furthermore, this method of defect reconstruction and seizing can be extended for irregular shape such as cracks and corrosion. In fact, this can be done while subdividing the affected area of non-constant depth into elementary zones of a constant depths. Then, while modifying the previous algorithm, we determine the corresponding depth of each zone.

Keywords: nondestructive testing, magnetic flux leakage, storage tank floor inspection, defect characterization.

RESUMO
O método MFL é uma ferramenta de inspeção qualitativa e é um método de teste não destrutivo confiável, rápido e econômico para pisos de tanques. Neste trabalho, antes de apresentar o procedimento de reconstrução de defeitos, estudamos o efeito dos parâmetros de defeitos no vazamento do campo magnético medido por um único sensor Hall. Tal como previsto, o estudo de cada parâmetro demonstrou que qualquer variação nos parâmetros geométricos do defeito em estudo induz um influxo significativo na amplitude e distribuição do sinal MFL; por esta razão, todos os parâmetros de defeito devem ser determinados com precisão e prudência. Depois disso, estudamos o desempenho da reconstrução da forma do defeito a partir de imagens do sensor MFL array e estimativa de profundidade usando um método de inversão iterativa. De fato, o primeiro estágio consiste em determinar a largura e o comprimento do defeito do mapeamento de vazamento de fluxo magnético reconstruído a partir dos sinais registrados dos sensores magnéticos micro-integrados. Como um segundo passo, após o acoplamento do software Comsol e Matlab, a profundidade do defeito é obtida acoplando o método de elementos finitos 3D e um algoritmo iterativo rápido recentemente desenvolvido. Consequentemente, a forma e o tamanho do defeito são obtidos após algumas iterações com um erro relativo inferior a 2%; o que torna este método muito apropriado para a reconstrução e quantificação de defeitos em tempo real. Além disso, este método de reconstrução e apreensão de defeitos pode ser estendido para formas irregulares, como rachaduras e corrosões. Na verdade, isso pode ser feito ao subdividir a área afetada de profundidade não
constante em zonas elementares de profundidades constantes. Então, ao modificar o algoritmo anterior, determinamos a profundidade correspondente de cada zona.

**Palavras-chave:** teste não destrutivo, vazamento de fluxo magnético, inspeção do piso do tanque de armazenamento, caracterização de defeitos.

1 INTRODUCTION

Storage tanks play a crucial role in storing both crude and refined oil, extensively employed in petroleum and chemical industries. Typically, the tank floor is constructed by welding multiple steel plates. Over extended periods of service, the tank floor is disposed to defects due to several factors such as pressure, temperature, and corrosion, (Peng et al., 2018). Magnetic Flux Leakage Nondestructive Testing (MFL-NDT) is an efficient method largely used to detect, classify, and characterize several anomalies such as surface breaking, corrosion, and deep defects, (Amos, 1996). When the ferromagnetic plate is saturated while using a permanent magnet, the presence of any defect in the specimen will distort magnetic flux distribution and cause magnetic flux leak into the air. Above the specimen surface, magnetic sensors are used to measure the leakage magnetic field, (Daniel et al., 2014). After that, the collected MFL signals are treated by deterministic, stochastic, or artificial intelligence to determine the defect shape, size, location, and orientation, (Ramuhalli et al., 2003). In the literature (Peng et al., 2018) the authors have analyzed the three-dimensional magnetic flux leakage signal of the ferromagnetic tank bottom plate through a finite element simulation experiment to establish the relationship between the three-dimensional component imaging and the defect length, width, and depth. However, the authors consider that for a determined edge-contour defect, the relationship between the average strength of a signal and the defect depth is linear. Still, we will explain by numerical simulation that this approximation is not acceptable for a large search domain and this generalization became not efficient in practice measurement, other authors Optimization of crack growth using eddy current tests and a genetic algorithm to estimate stress intensity factors (Aouissi et al., 2024).

Recently, other authors while using highly integrated three-dimensional magnetic sensors, used the least-square support-vector machine and particle
swarm optimization (PSO-LSSVM) algorithm to quantitatively identify the defects after noise reduction and converting the magnetic field information into color image information through pseudo-color imaging, (Zhijun et al. (2023). However, this method even if its robustness and precision aren’t suitable for real-time detection and quantification requires a very short calculation time. The objective of our article is to present a fast and precise approach of defect reconstruction based on MFL mapping and an iterative method that we have recently developed and applied in eddy current nondestructive testing and evaluation problems. In the first step, we determine the 2D rectangular defect geometrical parameters (length and width) from the coded and calibrated MFL mapping under Matlab software. Then, while knowing the previous parameters, we determine precisely and rapidly the defect depth by coupling the 3D Finite Elements Method (FEM) with a fast and efficient algorithm that we have already tested and used in the eddy current inversion problems, (Abbassi et al., 2020; Abdou et al., 2019).

2 MAGNETIC FLUX LEAKAGE NONDESTRUCTIVE TESTING

A storage tank primarily consists of welded ferromagnetic steel plates made of low-carbon steel. Corrosion of the bottom of the petroleum tank may lead to a product leak that could cause a fire or explosion resulting in damage to people and the environment, therefore the test of tank bottom corrosion is necessary to be conducted periodically to prevent the occurrence of the above problems, (Dang et al., 2020). Non-destructive testing of the tank's bottom plate is essential for evaluating the integrity of the storage tank (Shi et al., 2015; Hernandez et al. (2010). Currently, Magnetic leakage testing technology is largely used to detect, quantify, and classify all kinds of defects. Moreover, to discriminate top and bottom discontinuities the majority of MFL sensors are equipped with the Surface Topology Air-gap Reluctance System (STARS), (Neil, 2012).

The tank bottom plate made of low carbon steel is saturated by the exciting magnetic field. So, if a defect occurs on the upper and/or the lower surface the magnetic field will overflow the air at the defect and form a magnetic field leakage that will be captured by the magnetic sensors as shown in Figure 1.
In the MFL testing, the leakage magnetic field distribution for the defect of the nonlinear permanent magnetic system follows the basic law of the Maxwell equation (Zolfaghari; Kolahan, 2017), and the electromagnetic phenomenon can be expressed as follows.

\[ \nabla \times (\mu_0^{-1} \nabla \times A) = \nabla \times M \]  \tag{1} 

Where:

- \( A \) and \( M \) are the magnetic vector potential and magnetization, respectively.

The physical and geometrical dimensions of the basic MFL system are shown on Figure 2.
3 EFFECT OF THE DEFECT PARAMETER ON THE MAGNETIC FIELD DISTRIBUTION

After coupling Matlab and Comsol software, we implement the previous model. Then, we proceed to study of effect the defect length $L_d$, width $W_d$, depth $D_d$, and Lift-off on the magnetic flux leakage signal captured by the middle sensor. For this reason, we take four cases:

- Case #A: Defect length variation for $W_d = 8 \text{ mm}$ and $D_d = 4 \text{ mm}$.
- Case #B: Defect width variation for $L_d = 16 \text{ mm}$ and $D_d = 4 \text{ mm}$.
- Case #C: Defect depth variation for $W_d = 8 \text{ mm}$ and $L_d = 16 \text{ mm}$.
- Case #D: Lift-off variation for $W_d = 8 \text{ mm}$, $L_d = 16 \text{ mm}$ and $D_d = 4 \text{ mm}$.

The obtained results are given in Figure 3.
Through the obtained results, we notice that any variation in the defect parameters or Lift-off induces directly a modification in the magnetic field leakage. For this reason, the exploration of each parameter in the next sections must be done prudently.

**4 DETERMINATION OF THE DEFECT SHAPE AND SIZE FROM THE 3D MFL MAP**

To reconstruct the defect shape from the 3D MFL sensor array, we scan the steel plate from -40 mm to 40 mm with a step of 0.25 mm and we record the magnetic field leakage captured with the 17 Hall sensors. After that, we calibrate the defect area as the zone in which the magnetic flux leakage module is higher than 550 A/m. Then, we plot the corresponding 2D MFL map for two cases:

Case #1: the defect length at 100 mm and its depth at 4 mm while its widths are about 2 mm, 4 mm, and 8 mm as presented in Figure 4.
Figure 4. Defect parameters from MFL map. Case #1.

Case #2: the defect width is set at 4 mm and its depth at 4 mm while its lengths are about 50 mm, 100 mm, and 150 mm. The results are shown in Figure 5.
From the previous 2D MFL map, we can easily extract the defect length and width, analyze the obtained results, and discuss the precision of this approach. In fact, the obtained results are reported in Tables 1 and 2.

Table 1 Relative error according to defect width of 2 mm, 4 mm and 8 mm. Defect's length and depth are 100 mm and 4 mm.

<table>
<thead>
<tr>
<th></th>
<th>Actual parameters</th>
<th>Calculated parameters</th>
<th>E [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>La [mm]</td>
<td>Wa [mm]</td>
<td>Lc [mm]</td>
</tr>
<tr>
<td>Defect 1</td>
<td>100</td>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>Defect 2</td>
<td>100</td>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>Defect 3</td>
<td>100</td>
<td>8</td>
<td>110</td>
</tr>
</tbody>
</table>

Source: Authors.
Table 2 Relative error according to defect length of 50 mm, 100 mm and 150 mm. Defect's width and depth are of 4 mm.

<table>
<thead>
<tr>
<th>Defect</th>
<th>La [mm]</th>
<th>Wa [mm]</th>
<th>Lc [mm]</th>
<th>Wc [mm]</th>
<th>E [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect 1</td>
<td>50</td>
<td>4</td>
<td>50</td>
<td>4.25</td>
<td>6.25</td>
</tr>
<tr>
<td>Defect 2</td>
<td>100</td>
<td>4</td>
<td>90</td>
<td>4.25</td>
<td>4.375</td>
</tr>
<tr>
<td>Defect 3</td>
<td>150</td>
<td>4</td>
<td>150</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Authors.

\[
E(\%) = \left( \frac{\text{abs}(V_a - V_c)}{V_a} \right) \cdot 100
\]  
\[
V_a = L_a \cdot W_a \cdot D_a
\]  
\[
V_c = L_c \cdot W_c \cdot D_c
\]  

Where:

\( E \) is the relative error. \( L_a \) and \( L_c \) are the actual and the calculated defect lengths. \( W_a \) and \( W_c \) are the actual and the calculated defect widths. \( D_a \) and \( D_c \) are the actual and the calculated defect depths (\( D_a = D_c = 4 \) mm). \( V_a \) and \( V_c \) are the actual and the calculated defect volumes.

From the tables 1 and 2, we notice that as well as the defect size increase, it became detectable with high precision and the corresponding relative error decreases. On the other hand, we notice that when the defect width varies it induces a variation in its length and vice versa.

Also, in practice inspection equipment, using up to 128 sensors and high data acquisition frequency; the obtained relative errors will be significantly reduced. However, the defect depth remains unknown and must be calculated while knowing the previous parameters.

5 IMPLEMENTATION AND TEST OF THE DEFECT DEPTH ESTIMATION METHOD

In the following figures, we show the evolution of the field leakage as function as of the defect depth \( D_d \) (Figure 6. (A)). In order to simplify the representation of the signal as shown in Fig 6. (B), we plot the calculated mean
value \( H_{\text{mean}_c} \) of \( N \) Hall elements whose magnetic field value in the element \( i \) is \( H_i \).

Indeed, the mean value is given by the following expression:

\[
H_{\text{mean}_c} = \frac{\sum_{i=1}^{N} H_i}{N}
\]  

(5)

Looking at Figure 6, it is evident that \( H_{\text{mean}_c} \) increases according to the defect depth \( D_d \). In the literature (Peng et al., 2018), to determine directly the defect depth, the authors assimilated the curve shown in Figure 6.B to be linear. However, this approximation induce surely an addition error. For this reason, we conserve the nonlinearity of the curve and we use the fast inversion procedure which combines the 3D forward Finite Element Method (FEM) and the search algorithm that we have developed and applied to eddy current nondestructive testing (Helifa et al., 2016). So, this algorithm needs as inputs the measured magnetic flux leakage (\( H_{\text{mean}_{\text{mes}}} \)), the interval search limits (\( D_{d_{\text{min}}}, D_{d_{\text{max}}} \)), and the precision \( \varepsilon \), (Fig.7).

Figure 6. (A) Norm of MFL for different defect depth. (B) Average MFL value according to defect depth.

Source: Authors.
The developed inverse method was applied to determine the defect depth of the ferromagnetic tank floor plates. For three values of defect depth, the estimated value according to iteration number is shown in Figure 8.
The obtained results through the proposed method demonstrate that few iterations suffice to determine defect depths of 2.5 mm, 5 mm, and 7.5 mm with relative errors of 0.3125%, 0.15625%, and 0%, respectively. However, it is necessary to notice that the studied model doesn’t describe the actual defects encountered in practice inspection because surface breaking and corrosion do not necessarily have a parallelepiped shape. For this reason, as a future work, we will proceed to subdivide the defect area into elementary elements of unknown depths. Then, while using an appropriate inversion method, we reconstruct the defect shape after determining the elementary depths.

**6 CONCLUSION**

Magnetic flux leakage (MFL) testing is an electromagnetic nondestructive testing (NDT) method, that can detect various types of defects such as cracks, corrosion, pitting, and cavities, and it can detect both surface and subsurface defects. Therefore, it has been widely used to ensure the integrity and safety of structures in petroleum infrastructures such as tanks and pipes. During the MFL test, the defect is analyzed and evaluated on the basis of the MFL signal, which can provide a reference for the maintenance of the bottom of the storage tank. In this work, our contribution consists of developing a methodology taking into account the development of MFL array sensor testing technology through which
the results are represented in the form of images which makes it possible to determine the 2D defect shape. On the other hand, after determining the defect depth while using an appropriate algorithm, we can get easily the 3D defect profile and meet the real needs of NDT companies.

For this reason, in the first step we determine the 2D characteristics of a defect from the MFL 2D imaging. Then we proceeded to determine the defect depth while using an iterative algorithm that we have applied in eddy current nondestructive testing. Through this study, we have concluded that:

- determining precise defect shape and parameters from MFL information requires high-resolution image reconstruction. For this reason, the micro-integrated magnetic sensors with high data acquisition frequency are very appropriate.
- the proposed method in this work allow us the characterization of defects depth rapidly and precisely without any approximation and restriction.
- in comparison with the stochastic method (PSO, GA), the proposed method is more adapted for real-time characterization because few iteration numbers are sufficient for defect reconstruction.
- as future works, by looking to $H_{\text{mean}_c}(Dd)$, we can assimilate the curve to a linear function. Indeed, this will be able to guarantee a real time direct inversion without an iterative loop. On other hand, as we have done in other eddy current nondestructive testing problems, while using artificial intelligence tools we can use the MFL 2D images as inputs and the corresponding defect shape and dimensions as output in an augmented database, for defect classification and characterization, (Geng et al., 2022; Huang et al. (2023)).

However, the proposed algorithm of depth estimation is applicable only when the defect is of constant depth and must be generalized for irregular defect shapes of non-constant depth encountered in concrete inspections. In this case, the affected area must be subdivided into elementary zones. Then, while modifying the previous algorithm, we determine the corresponding depth of each zone.
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REFERENCES


