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Defect localization by orthogonally projected multiple signal classification approach for magnetic flux leakage fields

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ABSTRACT

Magnetic flux leakage technique is used for defect detection inside a magnetically permeable bar by measuring the leakage fields outside the bar. Defects of varying sizes in a magnetically permeable bar have been modelled as localized anti-dipoles with different moments. These defect locations and moments have to be determined based on the measurement of the leakage fields in the presence of random noise. Multiple Signal Classification (MUSIC) approach has been used to identify the defect locations and the moments of these defects. After finding the location of the first dipole representing the larger defect, using orthogonal projection of the measured magnetic field data away from the first defect location, location of the next dipole is identified by MUSIC. This process is continued until all the defects are exhausted. The leakage fields from three deeply buried defects were simulated by direct forward calculation and the resulting data were utilized for inversion using this approach. It has been possible to identify the number of defects and their locations by this approach even in the presence of reasonable levels of additive noise.

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1. Introduction

Magnetic flux leakage (MFL) method is widely used for non-destructive evaluation of defects in oil and gas pipelines manufactured from magnetic steels [1–3]. In MFL method, a static uniform magnetic field is applied to the magnetically permeable wall of the pipeline. Flaws in the pipe wall generate magnetic field perturbations which manifest as leakage fields outside the pipe. The technique involves the measurement of this leakage field profile and its offline evaluation to infer the locations of the defects and their size. A detailed description of defect modelling has been presented elsewhere [4,5]. Our objective is to determine the number of defects, their locations and the strengths of the dipoles that represent the defects from simulated leakage field measurements performed above the surface of the magnetically permeable structure. It has been possible to find a best estimate for the source using the generalized inverse or Moore–Penrose inverse approach [5,6], where the chosen solution minimizes the sum of the squared differences between the measured magnetic field and the field generated by the estimated source distribution provided the number of defects is known apriori. The Multiple Signal Classification (MUSIC) approach [6] has been utilized for identifying the dipole locations in magnetoencephalography (MEG) where the magnetic field is measured as a function of both space and time. The measured magnetic field $\boldsymbol{b}_z(x, y, z, t)$ is then a matrix with the number of columns greater than the number of dipoles making an assessment of number of dipoles possible by singular value decomposition (SVD). In MFL the magnetic field is measured only in terms of space variables and hence forms a single column vector. In view of this it is difficult to infer the number of dipoles involved in the problem by SVD. If the defects are well separated and the number of defects is unknown, we demonstrate that this inverse problem could still be handled to identify all the defect locations by MUSIC approach coupled with an orthogonal projection of the measured field data. After getting an estimate of the number of dipoles and their approximate locations, pseudo-inverse calculations are performed to get an improved estimate of the dipole locations and their strength.

2. Defect-induced magnetic leakage fields

The MFL due to a defect in a magnetically permeable material can be modelled as arising due to a dipole positioned at the defect site if the defect is a small cavity with a closed surface. The background magnetic flux density due to the magnetization of the sample does not contribute to the magnetic anomaly associated with the defect during scanning and is therefore ignored. The normal component of magnetic flux density $\boldsymbol{b}_z(x, y, z)$ for a dipole

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of strength m_x located at (x_0, y_0, z_0) and oriented towards the negative X-direction is given by [4,5]

$$\boldsymbol{b}_z(x,y,z) = \frac{-3\mu_0(x-x_0)(z-z_0)}{4\pi[(x-x_0)^2+(y-y_0)^2+(z-z_0)^2]^{5/2}} m_x \tag{1}$$

where μ_0 is the magnetic permeability of free space. An external magnetic field is applied in the positive X-direction to magnetize the bar and the defects are now modelled as dipoles with their magnetic dipole moments aligned along the negative X-direction. The Z component of the magnetic flux density $\boldsymbol{b}_z$ is sampled at a grid of points in the plane parallel to and above the top surface of the bar under investigation. The sampled magnetic field $\boldsymbol{b}_z(x,y,z)$ can be written as a product of a nonlinear function of space variables $\boldsymbol{M}(x,y,z,x_0,y_0,z_0)$ called lead matrix and the magnetic dipole intensity vector $\boldsymbol{Q}$ corresponding to the defect dipoles:

$$\boldsymbol{b}_z = \boldsymbol{MQ} \tag{2}$$

where $\boldsymbol{b}_z$ is a $m \times 1$ column vector corresponding to magnetic flux density at m different measurement locations, $\boldsymbol{M}$ is a $m \times q$ matrix where the different columns of the lead matrix $\boldsymbol{M}$ correspond to each of the assumed q dipoles and $\boldsymbol{Q}$ is a column vector of size $q \times 1$ corresponding to dipole moments of the q dipoles. In general the measurement locations m will be much larger than the number of dipoles q to be determined. To include noise, which is inevitably present in any experimental measurement, we write

$$\boldsymbol{b}_{zn} = \boldsymbol{MQ} + N \tag{3}$$

assuming an additive noise N. If the locations of the q defects and the strengths of the dipoles representing them are known apriori, the magnetic field due to all these defects can be calculated using the Eq. (3).

3. Generalized inverse procedure for identifying the location of defects

In actual measurements, $\boldsymbol{b}_z$ is measured at m locations whose coordinates are known; from these measurements, the locations and strengths of the dipoles have to be inferred. In general there is no unique solution to the above problem. However, it is possible to find an approximate solution which minimizes the least square error between the measured magnetic field and the field due to this approximate solution:

$$\|e\| = \|\boldsymbol{b}_{zn} - \boldsymbol{MQ}\|_F \tag{4}$$

where $\|\cdots\|_F$ represents the sum of the squares of the elements of the matrix, also referred to as the Frobenius norm [8]. The magnetic field due to the flux leakage as measured in an experiment which includes noise is then represented by the following equation:

$$\boldsymbol{b}_{zn} \cong \boldsymbol{M}'\boldsymbol{Q}' \tag{5}$$

where $\boldsymbol{M}'$ and $\boldsymbol{Q}'$ are approximate solutions obtained by minimizing $\|e\|$.

The Moore–Penrose inverse $\boldsymbol{M}'^{-1}_p$ provides us with the best estimate $\boldsymbol{Q}'$ in the presence of noise [8]. $\boldsymbol{Q}'$ can be expressed in terms of $\boldsymbol{b}_{zn}$ as follows:

$$\boldsymbol{Q}' = \boldsymbol{M}'^{-1}_p \boldsymbol{b}_{zn} \tag{6}$$

Inserting the relation (6) into Eq. (4) for minimizing the residual error we get

$$\|e\| = \left\|\boldsymbol{b}_{zn} - \boldsymbol{M}'\boldsymbol{M}'^{-1}_p \boldsymbol{b}_{zn}\right\|_F \tag{7}$$

The minimum norm solution of Eq. (7) also satisfies the Eq. (4) and hence the unknown position parameters in the lead matrix $\boldsymbol{M}'$ can be obtained directly by minimizing $\|e\|$ [5]. If the number of defects and their locations are known apriori, then $\boldsymbol{M}'$ can be constructed. Eq. (7) is a nonlinear minimization equation and can be minimized using a non-gradient based method such as Nelder–Mead simplex routine to get the unknown parameters contained in $\boldsymbol{M}'$, i.e. locations of the dipoles. Once the locations of the dipoles are obtained, the strengths of these dipoles $\boldsymbol{Q}'$ can be deduced by using Eq. (6).

4. Defect identification by MUSIC

If the measurement is carried out for different field strengths as well as measurement locations, $\boldsymbol{Q}$ is a matrix of size $q \times r$ where q is the number of dipoles and r is the number of sets of measurements, each set corresponding to a particular value of field strength ($r > q$ is assumed). In this case, $\boldsymbol{b}_{zn}$ will be matrix of size $m \times r$. Eq. (7) can be rewritten as follows:

$$\|e\| = \left\|(I - \boldsymbol{M}'\boldsymbol{M}'^{-1}_p)\boldsymbol{b}_{zn}\right\|_F \tag{8}$$

$$\|e\| = \|P_M^{\perp}\boldsymbol{b}_{zn}\|_F \tag{9}$$

where $P_M^{\perp}$ is the orthogonal projector of $\boldsymbol{M}'$ [8].

If $\boldsymbol{b}_{zn}$ is factorized into $[U \quad \Sigma \quad V^{\mathrm{T}}]$ by SVD [8] then $P_M^{\perp}$ can be approximated by $\boldsymbol{U}_{m-q}\boldsymbol{U}_{m-q}^{\mathrm{T}}$ [6] where $\boldsymbol{U}_{m-q}$ is the matrix comprising of the remaining m–q columns of the decomposed matrix $\boldsymbol{U}$ representing the noise subspace. To find the dipole locations by MUSIC approach [6], $\boldsymbol{G}_i$, the single dipole lead vector is factorized into $[U_i \quad \Sigma_I \quad V_i^{\mathrm{T}}]$ and the q column vectors of $\boldsymbol{U}_i$ at the left are represented as $\boldsymbol{U}_{iq}$ and constitute the signal subspace. In MUSIC approach the correlation between this signal subspace and noise subspace is minimized. The cost function J_{ls} [6] is the minimum of the eigen values of the product of signal subspace and noise subspace given by

$$J_{\mathrm{ls}} = \lambda_{\min}(\boldsymbol{U}_{iq}^{\mathrm{T}}\boldsymbol{U}_{m-q}\boldsymbol{U}_{m-q}^{\mathrm{T}}\boldsymbol{U}_{iq}) \tag{10}$$

The cost function J_{ls} when evaluated at dipole locations will yield near zero values for low noise data, whereas at all other locations the cost function will be nearly unity. To identify the positions of the dipoles in the presence of noise, the minimum eigenvalue cost function is evaluated in the region of interest (x, y, z coordinates) and the inverse of this cost function is plotted. Peaks in this graph indicate the positions of dipoles [6].

MFL measurements are in general carried out for only one field strength ($r = 1$) and hence the $\boldsymbol{b}_{zn}$ is a single column vector. This implies that $r < q$ and the single column vector $\boldsymbol{U}_i$ represents all the dipoles. However, It is still possible to infer the positions of all the dipoles provided one of the dipoles is dominant and the dipole locations are not very close. Then eigenvalue minimization of the above matrix Eq. (10) identifies the location of this dominant dipole. A better estimate of the dipole position is obtained by the generalized inverse procedure [5] for single dipole using the measured $\boldsymbol{b}_{zn}$. Having identified the location of the dominant dipole, the data $\boldsymbol{b}_{zn}$ is then orthogonally projected away [7] from this dipole by using

$$\boldsymbol{b}_{zn\perp 1} = (P_{\boldsymbol{G}_1}^{\perp})\boldsymbol{b}_{zn} \tag{11}$$

where

$$P_{\boldsymbol{G}_1}^{\perp} = I - (\boldsymbol{G}_1(\boldsymbol{G}_1^{\mathrm{T}}\boldsymbol{G}_1)^{-1}\boldsymbol{G}_1^{\mathrm{T}}) \tag{12}$$

is the orthogonal projection operator [8] of the dipole lead vector $\boldsymbol{G}_1$ corresponding to the first dipole. After projecting the measured magnetic field data away from the first dipole, the resultant $\boldsymbol{b}_{zn\perp 1}$ will have contributions predominantly due to the next most intense dipole. Repeating the search with MUSIC algorithm with the new $\boldsymbol{b}_{zn\perp 1}$ will yield the location of the second dipole. A better

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