Research on the magnetic flux leakage field distribution characteristics of defect in low-frequency electromagnetic detection technique

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Abstract This work aimed to investigate the distribution characteristics of the low-frequency magnetic flux leakage (LF-MFL) field of defect on oil and gas pipelines in low-frequency electromagnetic detection technique (LFET). Taking four types of crack defects (rectangular, semicircular, trapezoidal, and V-shaped grooves) with equal lengths, widths and different bottom shapes into consideration, the specific mathematical model of the LF-MFL field was inferred and established on the basis of magnetic dipole theory. Experimental results demonstrated that the variation values of the tangential and normal component upper-lower envelope difference curves were linearly positively correlated with the defect cross-sectional area along the detection direction, which was strictly independent of bottom shape and excitation conditions (amplitude, frequency and lift-off).

Keywords: low-frequency magnetic flux leakage (LF-MFL), low-frequency electromagnetic detection technique (LFET), magnetic dipole, cross-sectional area
Classification: Electromagnetic theory

1. Introduction

Low-frequency electromagnetic detection technique (LFET) is a new type of electromagnetic nondestructive testing method that was followed and developed in recent years. The unsaturated magnetization mode is adopted to detect the internal and external defects of ferromagnetic materials in LFET [1], which has the advantages of weak residual magnetism, small volume and conveniences. W.M. Lou et al. [2] and X.Y. Lu et al. [3] performed corresponding research on LFET and found that the amplitude and phase information of low-frequency magnetic flux leakage (LF-MFL) field can provide proof of the absence or presence of defects. Y. Chang et al. [4] implemented the design of excitation coil structures and found that with the increase in defect depth or excitation frequency, the C-type excitation coil shows a more obvious magnetic flux leakage field density than the U-type coil.

Generally, the defect location, size [5, 6], continuing direction [7] and shape on oil and gas pipelines are extremely crucial to later maintenance. So far, the LF-MFL field for different types of defects has not yet implemented and remains unclear in LFET because of the diversity of excitation conditions (mainly including the amplitude, frequency, and lift-off).

It is clear that the use of the unsaturated AC excitation method in LFET [8, 9, 10, 11] inevitably results in a weakened LF-MFL field at defects in the surface of inspected materials. An inductive magnetic coil [12, 13, 14, 15, 16] (LFET coil) is typically used as a substitute for traditional magnetic sensitive component [17, 18] to avoid disturbances from the external DC magnetic field, reflecting the tangential magnetic variation. Meanwhile, the high-sensitivity magnetoresistive (MR) sensor is always adopted as the signal acquisition medium [19, 20, 21], although it is affected greatly by spatial magnetic field. In addition, the magnetic dipole model [22, 23, 24, 25, 26, 27, 28, 29, 30] is one of the most mature theories used to explain the magnetic flux leakage field produced by an external DC or a permanent magnet, which can also directly analyze the relative change trend of LF-MFL field instead of the absolute value variation.

In this study, the mathematical models of the LF-MFL field spatial distribution for four types of groove crack defects (rectangular, semicircular, trapezoidal, and V-shaped) with equal lengths and widths were established on the basis of the derivation of magnetic dipole theory. Furthermore, a composite probe array combined with high-sensitivity MR sensors and LFET coils was also proposed as a medium for effectively picking up the absolute and relative signals of a spatial multi-dimensional magnetic leakage field. This approach can collect additional defect features and enable the comparison and analysis concerning the defect size, which provides the evaluation information of the defect corrosion degree.

2. Operating principle

As described in Fig. 1, LFET forms a low-frequency electromagnetic field in the inspected specimen by exerting alternating electric signals on the excitation coil. When it encounters the position of the defect or a reduction in wall thickness, the original distribution of the LF-MFL field will be changed.

The low-frequency alternating magnetic field strength of the excitation coil in Fig. 1 can be expressed as:

\[ H = H_0 \sin(2\pi ft + \varphi) \]  \hspace{1cm} (1)

where \( H_0 \) refers to the amplitude of the low-frequency al-
ternating excitation magnetic field, \( f \) and \( \varphi \) represent the driving frequency and initial phase, respectively.

Faraday’s law of electromagnetic induction states that the output signal of LFET coil is orthogonal to the original excitation signal, which can be described as:

\[
U = 2\pi f NS\mu_r \delta H_0 \cos(2\pi ft + \varphi') \tag{2}
\]

where \( N \), \( S \), \( \mu_r \), and \( \delta \) are the coil turns, cross-sectional area, relative permeability, and proportional coefficient of the LFET coil, respectively, \( \varphi' \) represents the phase of the received signal.

The output amplitude \((AU)\) and phase \((A\varphi)\) information of LFET coil can only reflect the tangential relative variation. Nevertheless, this variation can be applied to identify defects without being influenced by the DC magnetic field, even the AC magnetic field different from the excitation frequency. Meanwhile, the high-sensitivity MR sensor can directly exhibit the variation trend of the tangential and normal components of the LF-MFL field at defects, which can be regarded as absolute signals and provide data for the morphological analysis. However, the MR sensor is normally affected significantly by external spatial stray AC or DC magnetic field interference, which will change the magnetic field upper or lower envelop shape.

3. Magnetic dipole theory

In fact, the magnetic dipole theory is applicable to the occasion of saturation magnetization for the inspected material. Nevertheless, the relative variation trend of LF-MFL field in unsaturated LFET coil can also be analyzed. In addition, the defect opening width and length can be obtained by the composite probe array in Fig. 1. Therefore, in this paper, the four groove crack defects owning equal lengths, widths and different bottom shapes (rectangular, semicircular, trapezoidal, and V-shaped grooves) are considered as the magnetic dipole original models.

3.1 Rectangular, trapezoidal, and V-shaped crack defects

The rectangular and V-shaped groove defects can be regarded as an extension and analogy of the trapezoidal groove defect. Figure 2 exhibited two-dimensional cross-sectional model of the trapezoidal groove defect. Obviously, magnetic charge line density on both sides of the slot wall in the low-frequency electromagnetic excitation magnetic field can be set as \( \pm \sigma_s \sin \omega t \). Then, the magnetic field intensity \( d\vec{H}_1 \) from the left wall and \( d\vec{H}_2 \) from the symmetrical right wall at any spatial point \( P(i,j) \) above the defect can be respectively expressed as:

\[
d\vec{H}_1 = \frac{\sigma_s \sin \omega t dx}{2\pi \mu_0 r_f^2 - r_1^2}, \quad d\vec{H}_2 = -\frac{\sigma_s \sin \omega t dx}{2\pi \mu_0 r_f^2 - r_2^2} \tag{3}
\]

where \( \mu_0 \) and \( \omega \) represent the air permeability and angular frequency of the low-frequency excitation electromagnetic field, respectively, \( r_1 \) and \( r_2 \) are the direction vectors of the groove walls on both sides of the trapezoidal groove defect at \( P(i,j) \), \( \sigma_s \) and \( ds \) refer to the amplitude and microline element of the magnetic charge line density. The equations of the groove walls on both sides of the trapezoidal groove defect are expressed as \( x = -by/h - a - b \) and \( x = by/h + a + b \). Therefore, the numerical theoretical formulas of the tangential component \( H_x(x) \) and normal component \( H_y(y) \) at \( P(i,j) \) can be derived after depth integral calculation, as shown in Eqs. (4) and (5), respectively.

\[
H_x = \int_{-h}^{0} dH_{x1} + \int_{-h}^{0} dH_{x2} = \frac{\sigma_s \sin \omega t}{2\pi \mu_0 \sqrt{1 + b^2/h^2}} \cdot \frac{b}{h} \begin{bmatrix} \sinh(b(a+b+i)y) - \sinh(b(a-b+i)y) \noalign{\hline} \cosh(b(a+b+i)y) + \cosh(b(a-b+i)y) \end{bmatrix} \tag{4}
\]

\[
H_y = \int_{-h}^{0} dH_{y1} + \int_{-h}^{0} dH_{y2} = \frac{\sigma_s \sin \omega t}{2\pi \mu_0 \sqrt{1 + b^2/h^2}} \cdot \frac{b}{h} \begin{bmatrix} \sinh(b(a+b+i)y) + \sinh(b(a-b+i)y) \noalign{\hline} \cosh(b(a+b+i)y) - \cosh(b(a-b+i)y) \end{bmatrix} \tag{5}
\]

3.2 Semicircular groove crack defect

The specific numerical expression of the semicircular groove defect cannot be deduced by Eqs. (4) and (5). Nevertheless, the semicircular groove surface can be divided into \( n \) segments, and the starting and ending points of each segment are connected as the equivalent of the corresponding arc. A large value of \( n \) indicates that the semicircular groove section is close and that numerical calculation results with increased
accuracy can be obtained.

According to Fig. 3, for the \( m \)-th \((m = 1 \text{ to } n)\) arc segment on the left side wall, the coordinates of the start point and the end point are \((-r \cos (m - 1)\theta, -r \sin (m - 1)\theta)\) and \((-r \cos m\theta, -r \sin m\theta)\), respectively \((\theta = \pi /2n)\). Hence, the linear equation corresponding to the arc segment on the left wall and the equation at the symmetrical position on the right wall can be respectively expressed as \(x = ky + l\) and \(x = -ky - l\). Here, the parameters \(k\) and \(l\) can be shown as:

\[
k = \frac{\cos m\theta - \cos (m - 1)\theta}{\sin m\theta - \sin (m - 1)\theta}
\]
\[
l = \frac{-r [\sin (m - 1)\theta \cos m\theta - \sin m\theta \cos (m - 1)\theta]}{\sin m\theta - \sin (m - 1)\theta}
\]

Therefore, the tangential and normal components of the magnetic field intensity at \(P(i, j)\) can be expressed as:

\[
H_{sc} = \frac{\sin \omega t}{2\pi \mu_0} \sum_{m=1}^{n} \sigma_{sm} \left[ \left( \frac{1}{2} \right) \sqrt{1 + k^2} \ln \left( \frac{(j - \xi)^2 + (i + 1)^2 + k\xi (2i + k\xi + 2l)}{(j - \xi)^2 + (i - 1)^2 - k\xi (2i - k\xi - 2l)} \right) - r \sin (m - 1)\theta \right] -k \sin m\theta
\]

\[
H_{nc} = \frac{\sin \omega t}{2\pi \mu_0} \sum_{m=1}^{n} \sigma_{sm} \left[ \sqrt{1 + k^2} \left( \arctan \frac{l+i+k\xi}{\xi-j} + \arctan \frac{l-i+k\xi}{\xi-j} \right) -r \sin m\theta \right] -k \sin m\theta
\]

The tangential and normal component change curves about the rectangular \((a = 5 \text{ mm}, b = 0 \text{ mm}, h = 5 \text{ mm})\), trapezoidal \((a = 2 \text{ mm}, b = 3 \text{ mm}, h = 5 \text{ mm})\), V-shaped \((a = 0 \text{ mm}, b = 5 \text{ mm}, h = 5 \text{ mm})\) and semicircular \((r = 5 \text{ mm}, n = 360)\) groove defect can be obtained severally through numerical simulation on the basis of the foregoing theory analysis.

As described in Figs. 4 (a) and (b), the tangential components of those crack defects all reach their peaks at the center of the defect. In addition, the normal component reaches the positive peak at left boundary surface, then reaches a negative peak at right side. Undoubtedly, the regular pattern of the peak value follows the order of rectangular groove \((R) >\) semicircular groove \((S) >\) trapezoidal groove \((T) >\) V-shaped groove \((V)\).

4. Experiments and results analysis

4.1 Experimental platform

The length, width and height of the individual digital MR sensor (LIS3MDL, STMicroelectronics) in the composite probe described in Fig. 5 were 3, 3, and 1mm, respectively. And the single-channel LFET coil (the inner, outer diameter, and height were 1, 2.3, and 4 mm) was wound into a cylinder and embedded with a permalloy rod as coil core.

As shown in Fig. 6, a 10mm-thickness steel plate (Q235) engraved with a rectangular, semicircular, trapezoidal, and V-shaped groove crack defect was selected as the experimental object for simulating oil and gas pipeline. Figure 7 exhibited the established LFET experimental system, which was controlled to run at a constant speed of approximately 10 mm/s by a DC electric push rod and the scanning direction was perpendicular to the extension direction of crack defects.

4.2 Experimental results

The tangential and normal absolute LF-MFL signal curves above the defects picked up by single-channel MR sensor basically kept similar, all shown in Fig. 8. In this experi-

![Fig. 3 Two-dimensional cross-sectional model of semicircular defect](image3)

![Fig. 4 Change curves of the tangential component \(H(x)\) and the normal component \(H(y)\) of different types of defects](image4)

![Fig. 5 Actual composite probe with MR sensor and LFET coil array](image5)

![Fig. 6 Q235 steel plate with four cross-sectional crack defects](image6)
ment, the excitation amplitude, the driving frequency and the lift-off were uniformly set to 16V, 20Hz and 5mm (the lift-off was the minimum value due to the limitation of the installation size). In addition, the differences between the upper and lower envelope curves of the tangential and normal components in the defect scope from Fig. 8 were extracted for comparison and analysis, as shown in Figs. 9 (a) and (b). Unquestionably, the whole variation trends of tangential and normal component kept consistent with the numerical simulation results, which also presented the same rule of rectangular (R) > semicircular (S) > trapezoidal groove (T) > V-shaped groove (V).

As described in Fig. 10, the experiment results of LFET coil were equivalent to the tangential component difference curve variation of Fig. 9 (a), which had stronger anti-interference ability and could be considered as the basis for defect identification during the detection process.

Taking the tangential single-peak $\Delta H(x)$ and the normal double-peak $\Delta H(y)$ variation value described in Figs. 9 (a) and (b) into consideration, the related experiments about the influence factors (mainly including the excitation amplitude, driving frequency and lift-off) for the four types of groove defects were implemented. Figures 11, 12, 13 (a) and (b) exhibited the trends of $\Delta H(x)$ and $\Delta H(y)$ with different excitation amplitude, driving frequency and lift-off, respectively. It is clear that the whole variations presented...
The cross-sectional areas of the four types of groove crack defects at the position of single-channel MR sensor in Fig. 6 were 25, 35, 39 and 50 mm, respectively. As shown in Tables I, II and III, the correlation coefficients between the tangential, the normal component variations ($\Delta H(x)$ and $\Delta H(y)$) and the defect cross-sectional areas were all infinitely close to 1. In other words, the $\Delta H(x)$ and $\Delta H(y)$ were linearly positively correlated with the defect cross-sectional area. Here, the correlation coefficient ($\gamma_{\text{HIS}}$) formula could be provided by the following equation:

$$\gamma_{\text{HIS}} = \frac{\sum_{i=1}^{4} (\Delta H_i - \overline{\Delta H})(S_i - \overline{S})}{\left(\sum_{i=1}^{4} (\Delta H_i - \overline{\Delta H})^2\right)^{1/2} \left(\sum_{i=1}^{4} (S_i - \overline{S})^2\right)^{1/2}}$$

(10)

where $\Delta H_i$ represents the $\Delta H(x)$ and $\Delta H(y)$ under different excitation conditions, $S_i$ refers to the defect cross-sectional area, $\overline{\Delta H}$ and $\overline{S}$ are the average value of the corresponding parameter ($\Delta H_i$ and $S_i$), respectively.

5. Discussion

The defect length could be obtained from multichannel response signals of the composite probe array in Fig. 5, and the defect width could also be achieved from the time difference of the tangential or normal single-channel signal fluctuation (such as the variation curves in Fig. 9 (a) and (b)). However, the characterization of the depth or bottom shape remained unclear because of the diversity of detection conditions. Nevertheless, the calibration of inspected material with standard defects could be implemented before detection to clarify the relationship between the $\Delta H(x)$, $\Delta H(y)$ and excitation parameters (excitation amplitude, driving frequency and lift-off). Hence, a datasheet about the corresponding parameters would be formed. Then, the possibility of calculating the corrosion degree of inspected material could be provided due to the linear correlation law. In addition, during the process of scanning, the cross-sectional area along the detection direction within the defect volume covered by single-channel MR sensor could be regarded as the same because the sensor was small enough in length perpendicular to the defect detection direction. Accordingly, the more accurate corrosion degree evaluation would be obtained for the current position with the increase of the MR sensor array density.

6. Conclusion

The magnetic dipole theoretical models could accurately reflect the change trends of the tangential and normal component upper-lower envelope difference curves of the LF-MFL field at defect. And the LFET coil in composite probe was indispensable for the verification of the defect existence. Meanwhile, the variation values ($\Delta H(x)$ and $\Delta H(y)$) of the tangential and the normal component envelope curves picked up by MR sensor exhibited linear positive correlation with the cross-sectional area along the detection direction, which was independent of the defect bottom shape or excitation conditions, and could be used to predict the corrosion degree of oil and gas pipelines in later engineering applications.

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