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Weak magnetic flux leakage: A possible method for studying pipeline defects located either inside or outside the structures

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ABSTRACT

Magnetic leakage distribution results from linear defects of oil–gas pipelines in a weak magnetic field, which is modeled by the magnetic dipole theory. The analysis is useful for the identification of defects located either inside or outside the pipelines. The results indicate that the radial signals of inside–outside defects can be clearly distinguished, and the axial signals are basically the same in a weak magnetic field. The theoretical and the experimental results are very consistent.

1. Introduction

Oil and gas pipeline transportation plays a very important role in our national economy, and is referred to as “the main artery of energy circulation”. With the increase in service time, there exists a great potential risk for pipelines which may suffer from corrosion and damage caused by external forces and other problems. Among the traditional non-destructive testing methods, magnetic flux leakage (MFL) is the most popular method for in-line inspection of pipelines [1–3]. The MFL method can successfully overcome physical and practical inspection challenges presented by transmission pipelines, and MFL inner detector has been used to detect and measure corrosion defects, mechanical damages and cracks [4–6]. However, some questions are not solved completely, such as estimating flaw size, defect shape, the difference of inner–outer defects and so on [7–9]. Therefore, to improve the estimation precision of defects, many approaches have been studied. In this paper, we will provide a brief background on the weak magnetic field model to discuss the inspection and identification of inner–outer defects on oil–gas pipelines. The experiments carried out herein indicate that it is feasible to distinguish inner and outer defects. These results can provide a scientific basis for the improvement and practical application of the traditional pipeline MFL testing method.

2. Principle and basic structure

The MFL testing system is widely used to detect metal losses of the oil–gas pipelines [10–12]. In the system, the detecting module consists of a permanent magnet, magnetic yoke and Hall sensors. As shown in Fig. 1, the pipeline of interest is magnetized by a magnetic system with a permanent magnet and yoke to reach magnetic saturation, and then Hall sensors detect the leakage fields in the metal loss area.

All detected signals are sent to the computer by a USB interface. Fig. 2 shows the variation of the magnetic field, which can be achieved through the movement of the inner detector at a measured point. As the detector passes, the magnitude and direction of the magnetic field at the measured area is set out.

3. Mathematical model of leakage field distribution

The magnetic dipole is a basic magnetic unit. With characteristics of a different physical meaning and a clear geometric image, the magnetic dipole theory can be used to solve some theoretical problems in the traditional magnetic NDT area [13,14].

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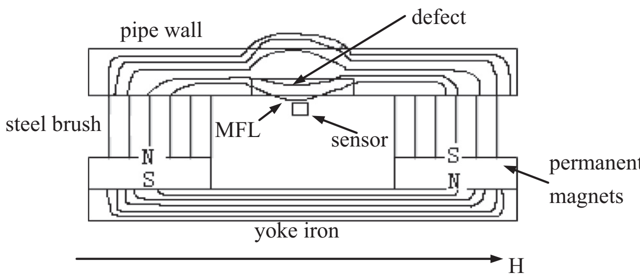

Fig. 1. Pipeline MFL detection main magnetic circuit.

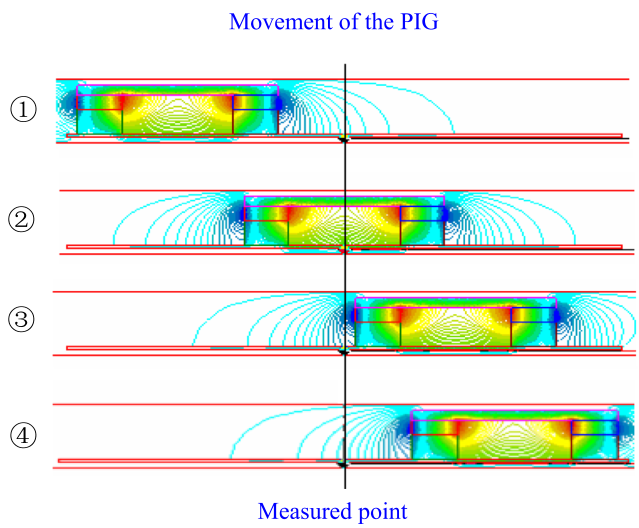

Fig. 2. Magnetic fields changes according to movement of MFL detector.

According to Coulomb's law, the model is established at a place which is deduced by the infinity analyzed object and the far magnetic field formula of the dipole [15]. However, MFL testing is carried out in the near surface of the magnetic charges, only involving the field characteristics. Therefore, the approximate solution of the far field has to be a small reference value, and the exact solution is suitable for investigating the near field characteristics of the magnetic dipole [16].

Under a strong magnetic field, the MFL signal depends mainly on the external magnetic field. It can be simulated by simplified two-dimensional models based on axisymmetric structures of pipelines. In a cylindrical coordinate system ($r \quad \theta \quad z$), Maxwell differential equations for the analysis of a static magnetic field are as follows:

$$\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(r\cdot A)\right]+\frac{\partial^2 A}{\partial Z^2}=-\mu J \tag{1}$$

Magnetic scalar and exciting current density only have circumferential components and can be regarded as scalars, and then the energy function equation can be created by a finite element model to solve the minimum of space energy, namely

$$F(A)=2\pi\iint_s \frac{1}{2\mu}B^2\cdot r d_r d_z-2\pi\iint_s JA r d_r d_z+2\pi\int_{L_2}\frac{1}{\mu}\left[\frac{1}{2}fA_1^2-fA_2\right]r d_l \tag{2}$$

Where, f expresses the exciting source of the magnetic field, s represents the magnetic field required, L_2 shows the boundary of the magnetic field space, $F(A)$ denotes the function equation, r refers to the radius and A_1, A_2 represents the boundary values of the magnetic field space. The models can be subdivided by a two-dimensional region Delaunay program. In any small unit$e$, vector magnetic potential can be shown as:

$$A=a_1+a_2 r+a_3 z \tag{3}$$

The magnetic potential values$A_i(r_i,z_i)$, $A_j(r_j,z_j)$and $A_m(r_m,z_m)$ on three nodes can be substituted into Eq. (3):

$$\begin{vmatrix}\alpha_1\\ \alpha_2\\ \alpha_3\end{vmatrix}=\frac{1}{2\Delta}\begin{vmatrix}\alpha_i & \alpha_j & \alpha_m\\ \alpha_i & \alpha_j & \alpha_m\\ \alpha_i & \alpha_j & \alpha_m\end{vmatrix}=\frac{1}{2\Delta}\begin{vmatrix}r_j z_m-r_m z_j & z_j-z_m & r_m-r_j\\ r_m z_i-r_i z_m & z_m-z_i & z_i-z_m\\ r_i z_j-r_j z_i & z_i-z_j & z_j-z_i\end{vmatrix} \tag{4}$$

Where, $\Delta=(1/2)(b_i c_j-b_j c_i)$, α_1, α_2 and α_3 in Eq. (4) can be substituted into Eq. (3), and then Eq. (5) can be obtained as follows:

$$A^e=A_i N_i^e+A_j N_j^e+A_m N_m^e \tag{5}$$

Where, A^e refers to the magnetic potential, $A_l(l=i,j,m)$ represents the coefficient of the basis function $N_l(l=i,j,m)$. In the unit e, B_r^e and B_z^e can be obtained for an axisymmetric pipeline system as follows:

$$B_r^e=-\alpha_3 \tag{6}$$

$$B_z^e=\frac{A}{r}+\alpha_2\approx\frac{A^e}{r^e}+\alpha_2 \tag{7}$$

Where, $r^e=(1/3)(r_i+r_j+r_m)$ and $A^e=(1/3)(A_i+A_j+A_m)$ are values in the center of e, so $[B^2]^e$ can be expressed as:

$$[B^2]^e=\alpha_2^2+\alpha_3^2+2\alpha_2\frac{A^e}{r^e}+\left|\frac{A^e}{r^e}\right|^2 \tag{8}$$

So $F(A)$ can be written as follows:

$$\begin{aligned}F(A)\approx\sum_{e=1}^{h}F^e(A)=\sum_{e=1}^{h}&\left|2\pi\iint_s\frac{1}{2\mu}[B^2]^e r d_r d_z-2\pi\iint_s JA r d_r d_z\right|\\&+2\pi\int_{L_2}\frac{1}{\mu}\left[\frac{1}{2}fA_1^2-fA_2\right]r d_l\\=\sum_{e=1}^{h}&(F_1^e+F_2^e)+F_3^e\end{aligned} \tag{9}$$

F_1^e and F_2^e can be obtained by the following equations:

$$F_1^e(A)=\frac{1}{2}[A_i \quad A_j \quad A_m]\begin{vmatrix}k_{ii} & k_{ij} & k_{im}\\ k_{ji} & k_{jj} & k_{jm}\\ k_{mi} & k_{mj} & k_{mm}\end{vmatrix}\begin{vmatrix}A_i\\ A_j\\ A_m\end{vmatrix}=\frac{1}{2}[A]^{e^T}[k]^e[A]^e \tag{10}$$

$$F_2^e(A)=[A_i \quad A_j \quad A_m]\begin{vmatrix}\frac{2\pi}{3}J_0 r^e\Delta\\ \frac{2\pi}{3}J_0 r^e\Delta\\ \frac{2\pi}{3}J_0 r^e\Delta\end{vmatrix}=[A]^{e^T}[P]^e \tag{11}$$

Boundary unit coefficient matrixes on the inhomogeneous natural boundary can be shown as:

$$[K]^e+[K']^e=\begin{vmatrix}K_{ii}^e & K_{ij}^e & K_{im}^e\\ K_{ji}^e & K_{jj}^e+\frac{\pi e l_0 f_1}{2}\left|r_i+\frac{r_m}{3}\right| & K_{jm}^e+\frac{\pi e l_0 f_1}{2}\left|r_i+\frac{r_m}{3}\right|\\ K_{mi}^e & K_{mj}^e+\frac{\pi e l_0 f_1}{2}\left|r_i+\frac{r_m}{3}\right| & K_{mm}^e+\frac{\pi e l_0 f_1}{2}\left|r_i+\frac{r_m}{3}\right|\end{vmatrix} \tag{12}$$

So the exciting matrix can be represented as follows:

$$[P]^e+[P']^e=\begin{vmatrix}\frac{2\pi}{3}J_0 r^e\Delta\\ \frac{2\pi}{3}J_0 r^e\Delta\\ \frac{2\pi}{3}J_0 r^e\Delta\end{vmatrix}+\begin{vmatrix}0\\ \frac{\pi e l_0 f_2}{2}\left|r_i+\frac{r_m}{2}\right|\\ \frac{\pi e l_0 f_2}{2}\left|r_i+\frac{r_m}{2}\right|\end{vmatrix} \tag{13}$$

Where, l_0 refers to the boundary length of each small unit. The system of linear equations about A_l on n nodes can be obtained by