

Research on magnetic signal of cracks in girth weld of ferromagnetic pipeline

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Abstract: The crack of pipeline girth weld is one of the most common and dangerous defects in girth weld. According to the magnetic dipole theory model, the magnetic signal model of pipeline girth weld cracks is established. By means of numerical simulation, the distribution characteristics of magnetic signals of crack defects in girth welds and the variation rules of magnetic signals of different flaw sizes and lifting heights of girth welds were studied. The simulation results show that the normal component H_y appears zero crossing and changes direction, and the tangential component H_x appears extreme value upward. Finally, the magnetic signal model of crack defects in pipeline girth weld was verified through field engineering test. The actual magnetic induction intensity detected at the flaw of pipeline girth weld was basically consistent with the theoretical calculation results, which verified the accuracy of the model.

Keywords: Girth weld; Crack defect; Weak magnetic detection.

1. Introduction

With the continuous development of modern industry, the demand for oil and natural gas is increasing. As the main energy in today's world, the transportation of petroleum and nature mainly relies on pipeline. Therefore, pipeline is also known as the main artery of industrial system and plays a vital role in the development of national economy [1]. With the construction of a large number of pipe networks, the safety of pipeline transportation is also faced with new challenges. There are many factors affecting the operation safety of girth welds, and the girth weld crack defect is the most common and dangerous factor in the failure of long-range pipeline and the ignition accident [2]. With the increasing length of oil and gas pipeline, the safety of pipeline operation becomes more and more important. The probability of internal corrosion occurring in a short time is very small for pipelines in service operation, and the anticorrosive layer and cathodic protection can effectively prevent external corrosion [3]. Therefore, the main problem faced by in-service pipelines, especially long-distance pipelines, is the ignition and explosion accident caused by girth weld defects [4]. The length of pipe section in long distance pipeline is generally about 12m, and the long distance oil and gas transmission pipeline and the pipeline of station and yard facilities along the pipeline are almost completed by welding process [5]. Therefore, welding of high-grade steel is the weak link of current long-distance pipelines [6]. The crack of pipeline girth weld is the most inadmissible defect in the safe operation of pipeline. When the crack of pipeline girth weld occurs, it is necessary to take reinforcing measures, and in serious cases, pipe change is needed [7]. It can be seen that the pipeline girth weld is the weak link of the pipeline safety system, and the girth weld crack is the weak part of the pipeline girth weld, so it must be tested regularly to ensure the long-term safe operation of the pipeline.

After Russian Professor Dubov[8] published the metal magnetic memory detection technology, the relevant research on weak magnetic detection at home and abroad followed. Based on magnetomechanical effects, Jiles and Atherton et al. [9] proposed A new force-magnetic coupling model: the J-A

model, which is widely accepted by relevant researchers because of its clear physical significance and simple calculation process. Hui Ding [10] established a mathematical model between the stress field of crack defects and the variation of magnetic flux, and studied the magnetic flux variation rules at different times such as crack burial depth, width, strike, stress condition and external magnetic field, which provided a theoretical basis for the weak magnetic field detection of crack defects. However, only one crack type was discussed and the influence of crack length on magnetic field was not considered. Xinjie Di [11] used wavelet transform and Fourier transform to filter the magnetic signal, obtained the criterion for determining the existence of crack defects, proposed a new crack mechano-magnetic coupling model, and studied the relationship between the depth and length of the crack and the maximum principal stress, but did not study the relationship between the crack intensity factor, the characteristic parameters of the crack and the magnetic field. Bingyan Huang [12] proposed a new mathematical model of the mechano-magnetic coupling of cracks, and analyzed the magnetic field of pipeline cracks by ANSYS finite element simulation.

Based on magnetic dipole model, a magnetic signal model for crack defects of pipeline girth weld is established in this paper. The effects of different crack sizes and different lifting heights on magnetic induction distribution of crack defects were studied by numerical simulation, and the numerical simulation results were verified by field detection data. The results show that the distribution characteristics of magnetic induction intensity obtained by this model can judge the crack defects of pipeline girth weld, and provide a new idea and method for the periodic risk investigation of pipeline girth weld crack defects.

2. Crack magnetic signal model

Due to the stress concentration, the reverse magnetostriction effect is generated in the buried ferromagnetic pipeline under the action of the geomagnetic field and the domain structure is changed, so that the permeability at the crack defect changes. Due to the difference in permeability between ferromagnetic pipe and

crack gap, self-leakage magnetic field will be generated when magnetic force line passes through the crack defect. Magnetic dipole model based on crack leakage magnetic field generated by dipoles of opposite polarity [13], to equivalent crack defects. See Figure 1-1.

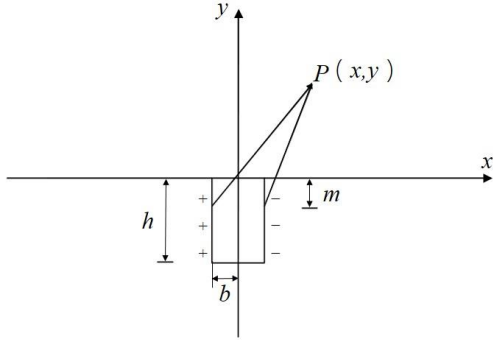


Figure 1. Magnetic dipole model of crack

It is assumed that the flaw depth of the crack is h and the length is $2b$. The magnetic charge is distributed on the two walls of the crack defect to form a magnetic dipole with surface density of ρ_m , depth coordinate of $-m$ and width of dm . According to the knowledge of electromagnetism, the magnetic field intensity generated by the element at any point P in space is shown in the following equation 1.

$$\begin{cases} dH_1 = \frac{\rho_m dr_1}{2\pi\mu_0 r_1^2} r_1 \\ dH_2 = \frac{\rho_m dr_2}{2\pi\mu_0 r_2^2} r_2 \end{cases} \quad (1)$$

r_1 and r_2 can be obtained from Figure 1: $r_1 = \sqrt{(x+b)^2 + (y+m)^2}$; $r_2 = \sqrt{(x-b)^2 + (y+m)^2}$; Then the components of dH_1 and dH_2 in the x and y directions in the rectangular coordinate system are respectively dH_{1x} , dH_{1y} , dH_{2x} and dH_{2y} :

$$dH_x = dH_{1x} - dH_{2x} = \frac{\rho_m (x+b) dm}{2\pi\mu_0 [(x+b)^2 + (y+m)^2]} - \frac{\rho_m (x-b) dm}{2\pi\mu_0 [(x-b)^2 + (y+m)^2]} \quad (2)$$

$$dH_y = dH_{1y} - dH_{2y} = \frac{\rho_m (y+m) dm}{2\pi\mu_0 [(x+b)^2 + (y+m)^2]} - \frac{\rho_m (y+m) dm}{2\pi\mu_0 [(x-b)^2 + (y+m)^2]} \quad (3)$$

The total magnetic field intensity can be obtained by integrating the equations (2) and (3) in the x and y directions respectively:

$$H_x = \int_{-h}^0 dH_{1x} - \int_{-h}^0 dH_{2x} \quad (1-4)$$

$$= \int_{-h}^0 \left(\frac{\rho_m (x+b) dm}{2\pi\mu_0 [(x+b)^2 + (y+m)^2]} - \frac{\rho_m (x-b) dm}{2\pi\mu_0 [(x-b)^2 + (y+m)^2]} \right)$$

$$H_y = \int_{-h}^0 dH_{1y} - \int_{-h}^0 dH_{2y} \quad (1-5)$$

$$= \int_{-h}^0 \left(\frac{\rho_m (y+m) dm}{2\pi\mu_0 [(x+b)^2 + (y+m)^2]} - \frac{\rho_m (y+m) dm}{2\pi\mu_0 [(x-b)^2 + (y+m)^2]} \right)$$

Where:

H_x : component of magnetic field intensity along the x axis generated by the defect at point P ;

H_y : component of magnetic field intensity along the y axis generated by the defect at point P .

The relationship between magnetic charge density ρ_m and magnetization intensity M is as follows:

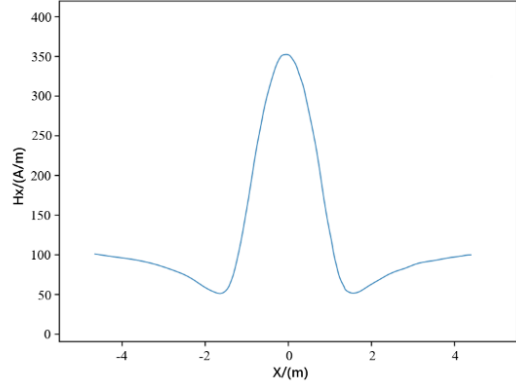
$$\rho_m = \mu_0 M \quad (6)$$

Where:

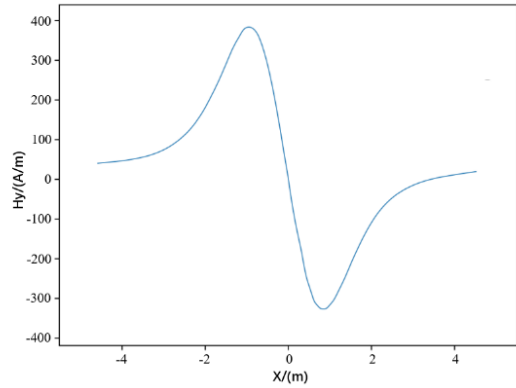
ρ_m : magnetic charge density; μ_0 : vacuum permeability.

3. Simulation result analysis

According to relevant parameters, formula (6) is substituted into formula (4) and (5). Let's take $b=2\text{mm}$; $h=1\text{mm}$; The height from the ground $y=2\text{m}$. The tangential component H_x and the normal component H_y of the magnetic signal of the crack defect of the girth weld are obtained by calculation, and the calculation results are shown in Figure 2.



(a) Tangential component waveform diagram



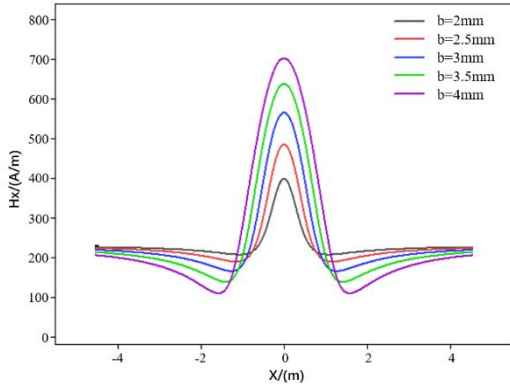
(b) Normal component waveform diagram

Figure 2. Calculation results of magnetic signal model of crack

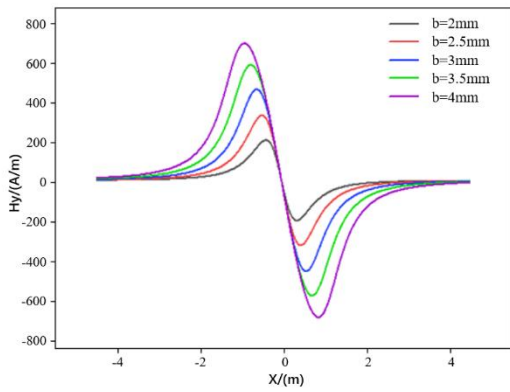
As can be seen from Figure 2, the distribution characteristics of tangential and normal magnetic signals of cracks in pipeline girth weld are as follows: the tangential component H_x shows an upward extreme value, while the normal component H_y shows a zero crossing and changes direction.

3.1. Effect of crack size

In order to study the influence of different crack lengths on magnetic signals, the normal and tangential components of magnetic memory signals with crack lengths b of 2mm, 2.5mm, 3mm, 3.5mm and 4mm were calculated respectively, as shown in Figure 2-2. As can be seen from Figure 3, when the crack length increases from 2mm to 4mm, the magnetic signal of tangential component H_x and normal component H_y increases significantly. In this process, the tangential component H_x maintains an upward extreme value feature, while the normal component H_y maintains a zero crossing feature and changes direction.



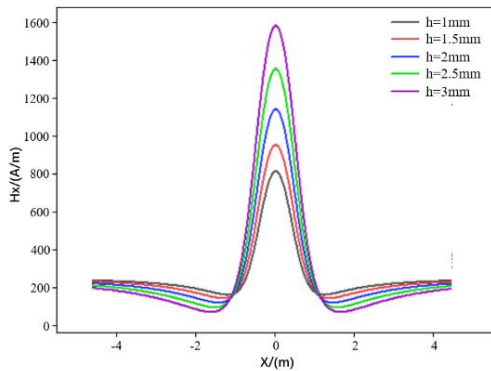
(a) Tangential component waveform diagram



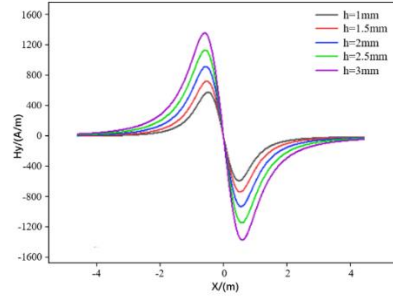
(b) Normal component waveform diagram

Figure 3. Waveform of magnetic memory signal with different crack lengths

In order to study the influence of different crack depths on magnetic signals, the normal and tangential components of magnetic memory signals were calculated when the crack depth h was 1mm, 1.5mm, 2mm, 2.5mm and 3mm, as shown in Figure 4. As can be seen from Figure 4, with the crack depth increasing from 1mm to 3mm, the magnetic signal of tangential component H_x and normal component H_y increases significantly. In this process, the tangential component H_x maintains the extreme value feature of upward direction, while the normal component H_y maintains the feature of crossing zero and changing direction.



(a) Tangential component waveform diagram

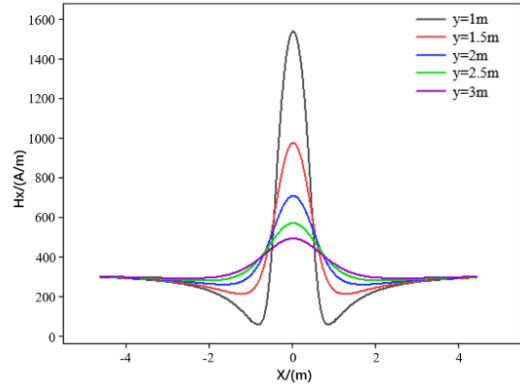


(b) Normal component waveform diagram

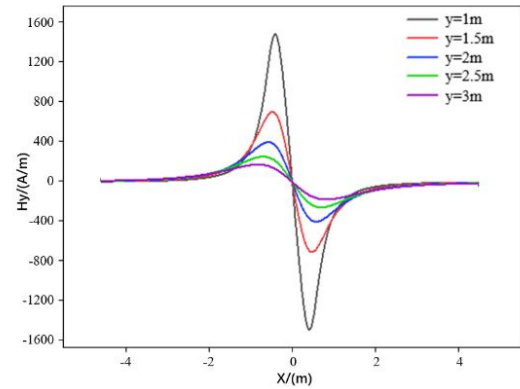
Figure 4. Waveform of magnetic memory signal with different crack depths

3.2. The effect of different altitudes above the ground

In order to study the influence of different elevations on magnetic signals, the normal and tangential components of magnetic memory signals with different elevations y of 1m, 1.5m, 2m, 2.5m and 3m are calculated respectively, as shown in Figure 5. As can be seen from Figure 5, the magnetic signal of tangential component H_x and normal component H_y decreases significantly as the height off the ground increases from 1m to 3m. When the height off the ground increases from 1m to 1.5m, the magnetic signal decreases the most; when the height off the ground increases from 2.5m to 3m, the magnetic signal decreases the least.



(a) Tangential component waveform diagram



(b) Normal component waveform diagram

Figure 5. Waveform of magnetic memory signal with different lifting values

4. Field test

Select a pipeline transport branch line in a high-risk area for detection. Pipeline detection process: pipeline positioning and marking; Magnetic signal detection and data collection; Data processing; Table 1 lists the pipe information and test records and reports.

Table 1. Pipe information

pipeline specification/ (mm)	pipe material	Transport medium	design pressure/ (MP)	operating pressure/ (MPa)
Φ1016×14.6	X70	Natural gas	12	11

Test instruments are used to test pipelines, and test data are drawn into waveform graphs, as shown in Figure 6. Through the analysis of waveform diagram changes, combined with the simulated crack defect waveform diagram, select the excavation point.

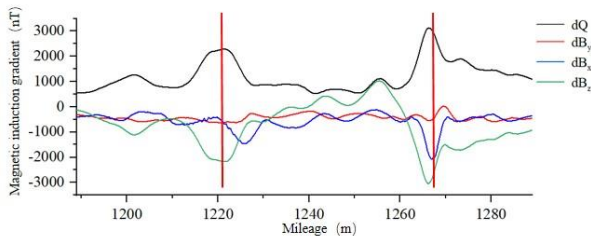


Figure 6. Field test data

Through the excavation combined with the routine inspection of the pipeline girth weld, the X-ray inspection results show that there are cracks in the pipeline girth weld at Z141+1221m and Z141+1267m. Therefore, the magnetic signal characteristics of cracks detected in practice are in good agreement with the numerical calculation results. The difference is that the magnetic induction gradient value in the direction of the numerical calculation method is strictly zero crossing, while the drift phenomenon exists in the actual detection of the normal direction zero crossing characteristics.

5. Conclusion

In this paper, the magnetic signal model of crack defects in pipeline girth weld was numerically simulated, and the influences of different crack sizes and different ground heights on magnetic signals were analyzed. The numerical simulation results were verified with field test data, and the following conclusions were drawn.

(1) The crack defects of the pipeline girth weld were analyzed through the deduced magnetic signal model of the pipeline girth weld, and the magnetic signal distribution law of the crack defects of the pipeline girth weld was obtained, that is, the zero-crossing feature appeared in the magnetic induction gradient of the pipeline upward method, and the maximum feature appeared in the tangential magnetic induction intensity.

(2) The influences of different factors on magnetic signals are analyzed. The distribution characteristics of magnetic signals in the pipeline are similar to that of magnetic signals when crack depth changes and crack length changes, and the magnetic signals increase in different degrees with the

increase of crack characteristic parameters. The difference is that the magnetic signals increase more significantly when crack depth changes than when crack length changes. In short, the magnetic signal of the pipeline is more sensitive to the crack depth change, and the higher the height from the ground, the weaker the magnetic signal.

(3) The magnetic signal characteristics of pipeline girth weld crack defects were verified through field detection test, and the accuracy of crack magnetic signal model was verified. The feasibility of non-contact detection of girth weld crack defects of buried ferromagnetic pipeline could be realized through this model.

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