Simulation Study on Pipeline Deformation Defect Detection Based on Eddy Current Effect

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Abstract. Oil and gas pipeline deformation detector is of great significance for pipeline deformation detection. In view of the poor throughput of small diameter oil and gas pipelines, this paper presents an internal deformation detection technology based on eddy current effect. Based on the eddy current theory, a mathematical model for eddy current testing of pipeline deformation defects is established. The relationship between probe lift-off value and magnetic field intensity is studied by numerical calculation method. The results show that under the same lift-off value, the composite magnetic field intensity is negatively correlated with the axis distance of the excitation coil, and at the same position, the composite magnetic field intensity is positively correlated with the lift-off value. The research in this paper has certain guiding significance for the internal detection technology of pipeline deformation defect.

1. Introduction

Pipeline deformation detection technology, as an important means of pipeline detection, is of great significance. For new pipelines, deformation detection is an important means of pipeline quality testing and acceptance; for existing pipelines, pipeline deformation will increase oil resistance, reduce pipeline strength, and increase the probability of stuck accident in pipeline inspection equipment.

Small-caliber oil and gas pipelines have low throughput, so there are more stringent requirements for the size of pipeline inspection equipment. Traditional deformation detection equipment is contact type, and its passing capacity is relatively low. Its working principle is that one end of the mechanical inspection arm arranged along the axis of the inspection equipment is in close contact with the pipeline under the elastic force of the supporting spring, the other end is placed on the base and attached with magnets. The fixed magnetic rotary encoder on the base records the rotation angle of the inspection arm to detect the deformation of the pipeline. In this way, a single sensor detects the deformation of a point on the pipe wall, and the detection range is too small. At the same time, the mechanical inspection method increases the weight and radial dimension of pipeline inspection equipment, so it is not conducive to the deformation detection of small diameter pipelines.

Compared with traditional pipeline deformation detection technology, eddy current detection technology has higher detection resolution, and does not need coupling agent, and does not contact with the pipe wall[1]. Eddy current testing equipment is smaller in volume and lighter in weight. Therefore,
The application of eddy current testing equipment in pipeline inspection will reduce the risk of blocking and achieve the goal of small-caliber pipeline inspection[2].

Based on the above background, this paper carries out numerical simulation research on pipeline deformation detection based on electromagnetic eddy current effect to verify the accuracy and feasibility of eddy current deformation detection.

2. Deformation defect internal detection theory based on Eddy Current Effect

2.1. Structure and working principle of eddy current deformation internal detector

As shown in Figure 1 above, the floating eddy current deformation detector mainly includes: 1 collision head, 2 leather bowls, 3 rigid skeleton, 4 eddy current detection probe, 5 electronic storage, 6-mile wheel and so on. Anti-collision head has the function of preventing rigid impact and cushioning; while the axis of the detector is coincident with the axis of the pipeline, the pressure difference between the front and back of the detector is established to provide power for the detector; the rigid framework provides support for the whole detection equipment; the eddy current sensor is used to detect the deformation of the pipeline; the electronic warehouse is used to place the power supply and data storage module; and the odometer wheel is used to record the odometer information of the equipment.

The mechanism of eddy current sensor to detect pipeline deformation is shown in Fig. 2. The excitation coil is fixed on the rigid skeleton with sinusoidal alternating voltage signal, which generates a primary alternating magnetic field $H_1$. The detection element is flexibly connected with the inner detector skeleton and closely fits with the pipe wall. The secondary magnetic field $H_2$ produced by the deformed pipeline under the excitation of a primary magnetic field is located at the distance excitation coil $d$, and the intensity of the composite magnetic field is detected, so as to calibrate the relationship between the peak intensity of the composite magnetic field and the distance $s$ between the testing element and the tested pipe, so as to achieve the purpose of detecting the pipeline deformation.

2.2. Establishment of mathematical model

According to 2.1, the theory of eddy current ranging is the basis of eddy current ranging. The simplified eddy current ranging model is analyzed below.
As shown in Fig. 3, the measured element is a metal plate model. A sinusoidal signal with an amplitude of $I_m$ and a frequency of $f$ is used as the excitation signal in the excitation coil. The excitation coil generates eddy current at the position shown in the figure on the surface of the metal plate. Suppose that the distance between the excitation coil and the metal plate is $h$, the thickness of the metal plate is $t_0$, the relative permeability is $\mu_r$ and the conductivity is $\sigma$. Suppose that the penetration depth does not exceed the thickness of the metal plate under ideal conditions[3].

At this moment, the magnetic field strength $H$ on the surface of the metal plate is:

$$H(x, y, z) = H_1(x, y, z) + H_2(x, y, z)$$ (1)

In which the excitation coil is placed in the air and the primary excitation field is produced by the excitation coil. The secondary magnetic field produced by a metal plate under the excitation of a primary magnetic field, when the lift height is $h$, the magnetic field intensity generated by the excitation coil on the metal surface for:

$$H_{hk} = \frac{I}{2\pi h(X/h)^2}$$ (2)

The secondary magnetic field generated on the surface of a metal plate can be expressed in Fourier differential form as follows:

$$H_2(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_i(u, v) e^{j(\sqrt{u^2 + v^2})} e^{-j(ux + vy)} \, du \, dv \quad (Z=0, \ i=x, y, z)$$ (3)

In the formula above, the coefficient $A_i$ ($i=x, y, z$) is expressed as follows:

$$A_x(u, v) = \frac{\mu \lambda B}{jkQ} e^{\lambda u} (\lambda + \mu k) - e^{\lambda u} (\lambda + \mu k) \cdot H_{2y}(u, v)$$ (4)

$$A_y(u, v) = \frac{\mu \lambda B}{jkQ} e^{\lambda v} (\lambda + \mu k) - e^{\lambda u} (\lambda + \mu k) \cdot H_{2z}(u, v)$$ (5)

In the formula above $\lambda, k, B, Q$ are expressed as:

$$\lambda = \sqrt{u^2 + v^2 + \frac{j2\pi \mu \lambda}{\mu \sigma}}$$ (6)

$$A_x(u, v) = \frac{\mu \lambda B}{jkQ} e^{\lambda k} (\lambda + \mu k) - e^{\lambda k} (\lambda + \mu k) \cdot H_{2x}(u, v)$$ (7)

$$k = \sqrt{u^2 + v^2}$$ (8)

$$B = j\mu H_{2x}(u, v) + j\nu H_{2y}(u, v) + kH_{2z}(u, v)$$ (9)

Fig 3. Principle diagram of eddy current detection
Of which, \( H_{2,x}, H_{2,y}, H_{2,z} \), \( H_2(x, y, 0) \), \( H_{2,z}(x, y, 0) \) are Second-order Fourier transform.

\[
Q = e^{\alpha s} (\lambda + \mu k)^2 - e^{-\alpha s} (\lambda - \mu k)^2
\]  

(10)

According to the theoretical analysis, the composite magnetic field strength can be calculated quantitatively with known excitation parameters, lift-off value \( H \) and metal sheet material properties.

3. Numerical simulation of deformation defect detection

3.1. Model establishment

Jiang He of Huazhong University of Science and Technology studied the similarity between the pipeline model and the flat model. When the radius of the pipeline is large, the flat model can be used to replace the pipeline model for numerical simulation, which has little influence on the accuracy of numerical simulation. Based on this conclusion, the flat model is used to replace the pipeline detection model, and the simulation model sketch is shown in Figure 4 below[4].

![Figure 4. Simplified sketch of simulation model](image)

3.2. Numerical calculation

The parameters are as follows: inner diameter \( \Phi_1=20 \)mm, outer diameter \( \Phi_2=30 \)mm, height \( h=10 \)mm, turn number \( N=300 \), conductivity of copper coil=5.8×10^7 S/m, relative permeability=0.99; location of detection element is close to tube wall, length is 30mm; conductivity of tube wall material measured is 2×10^6 S/m, relative permeability=1, thickness of specimen is 7mm, loading voltage is 2V, detection frequency \( f=100 \) Hz.

![Figure 5. Schematic diagram of numerical simulation](image)

As shown in the figure below, the distance \( d=2 \)mm between the fixed excitation coil and the detection element is unchanged, and the distance \( s \) between the test plate and the detection element is changed to 1mm, 2mm, 3mm, 4mm and 5mm in turn. The magnetic induction intensity of A1, A2, A3 and A4 (from right to left) points changes with time under different lift-off values \( s \).

3.3. Simulation results and analysis

As shown in Fig. 6, when the lifting height is 1 mm, the composite magnetic field intensity changes with time. The analysis shows that the intensity of the composite magnetic field decreases with the increase of the distance from the axis of the excitation coil.
As shown in Fig. 7, the magnetic field intensity at A1 is relatively small, and at A2, A3 and A4 is relatively strong. Because of the weak secondary magnetic field generated by eddy current and the existence of simulation errors, it is difficult to get the relationship between lifting height s and peak variation of composite magnetic field intensity by analyzing A2, A3 and A4 points (shown in Fig. 7, b, c and d); as shown in (a), the primary magnetic field intensity at A1 is small and complex. The combined magnetic field intensity is greatly influenced by eddy current, and the peak value changes obviously with the change of s value.

In order to further obtain the variation law between the peak value and lift-off height, the peak value of A1 point at each lift-off height was extracted, and the corresponding relationship.

![Figure 6. Changes of magnetic field intensity at A1, A2, A3 and A4 points with time at elevation of 1 mm.](image)

![Figure 7. Time-dependent curves of magnetic induction at different lift-off values, points A1, A2, A3, A4.](image)

**Table 1. Different positions of magnetic field intensity amplitude changes with time**

| Position | A1      | A2      | A3      | A4      |
|----------|---------|---------|---------|---------|
| s1       | 0.000147| 0.005483| 0.006852| 0.006865|
| s2       | 0.000171| 0.005506| 0.006864| 0.006879|
| s3       | 0.000180| 0.005511| 0.006875| 0.006890|
| s4       | 0.000188| 0.005515| 0.006882| 0.006894|
| s5       | 0.000191| 0.005521| 0.006889| 0.006906|

The relationship between lift-off height and the peak value of magnetic field intensity was established. As shown in Table 1 and Figure 8:
Figure 8 shows that the peak value of magnetic field intensity is positively correlated with lift-off height. It can be seen intuitively that when lift-off value is small, the change of wave peak value is large, and when lift-off value is large, the change of wave peak value is small[5]. The obtained of A1 data are fitted by polynomials:

\[ Y = 7 \times 10^{-7}x^3 - 1 \times 10^{-5}x^2 + 5 \times 10^{-5}x + 0.0001 \quad (R^2 = 0.9967) \]

The fitting degree is good. It can be concluded that the variation of peak magnetic field intensity and lift-off value presents a polynomial law, and the slope of change curve decreases in turn[5].

4. Conclusion
This paper presents a pipeline deformation detection model based on eddy current effect. According to the theory of electromagnetic field, the mathematical model of eddy current distance measurement is deduced. It is proved that the composite magnetic field strength, lift-off value, material properties and thickness of metal plate can be calculated quantitatively under the condition of parameters.

In this paper, the model of eddy current detection distance is established by finite element method, and the variation of peak value and rise value of composite magnetic field is simulated. The results show that when other conditions remain unchanged, the peak value of magnetic induction increases with the increase of the rise value, decreases with the increase of the rise height when the rise height is small and the change of the peak value of magnetic field is obvious.

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