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Parametric Study on the Pipeline Stress Detection of Magnetostrictive Guided Wave

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Abstract

The corrosion of pipelines caused by concentrated stress is a main cause of pipeline leakage when long-distance oil pipelines are laid in complex environment. Regular inspection of pipeline stress can prevent the further aggravation of pipeline corrosion caused by stress at early minor defects. Aiming at the problem of pipeline stress damage detection, this research simulatesthe pipeline stress detection based on the magnetostrictive guided wave technology. Firstly, on the basis of the echo signal generated at the defect location of the pipeline, the solution process of the electromagnetic field of the ferromagnetic material is analyzed by the physical equation. Secondly, the stress detection model of straight pipe segment is built with the help of COMSOL software. Finally, the effect of depth, width and excitation frequency of the corrosion defect on the stress state are analyzed by finite element simulation. The results show that the magnetic induction strength inside the ferromagnetic material determines the strain size of the material under the action of an external magnetic field. Under the same excitation condition, the stress at the defect increases with the depth of the defect and decreases with the increase of the axial width. Under the condition that the defect is unchanged, the stress increases with the increase of the excitation frequency, and decreases with the increase to a certain extent. In this paper, a method of stress detection with magnetostrictive guided wave is presented to realize the purpose of concentrated stress detection at early defects, which is of significance to reduce the risk of pipeline leakage.

Keywords

Pipeline defect; magnetostrictive effect; finite element simulation; stress detection; guided wave detection.

1. Introduction

Pipeline transportation has the advantages of high efficiency, durability, safety and reliability, and has become the main mode of energy transportation in China [1-2]. As the oil pipeline has been exposed to the external complex environment for a long time, the pipe wall is gradually aging in the complex environment over time, which leads to frequent failure accidents of the oil pipeline [3-4]. The stress concentration of the pipeline is easy to cause the pipeline wall thinning. Therefore, the stress detection of oil and gas pipeline has received great attention. In order to effectively detect the stress state of the pipeline and prevent the stress from further corroding the pipeline, more accurate and convenient pipeline stress detection technology is needed.

At present, the technology based on electromagnetic stress measurement is widely used in the stress detection of ferromagnetic materials [5]. Common methods of magnetic stress measurement mainly include hysteresis effect method, Barkhausen effect method, ultrasonic stress wave method, stress-induced magnetic anisotropy and nonlinear harmonic method [6-

10]. The weak magnetic stress detection technology is mostly used for the internal detection of pipeline stress, that is, the pipeline stress is detected by obtaining the weak magnetic signal on the pipeline surface. However, due to the complex stress on the pipe wall and the influence of the external environment on the detection signal, such as geomagnetic field and underground cables will produce varying degrees of interference on the weak magnetic signal, which will bring some difficulties to obtain the accurate signal. Therefore, the electromagnetic stress detection technology under the reverse magnetostriction effect is applied. The signal generated in the detection technology is stable, not easy to be disturbed by the outside world, and has strong recognition ability. It has good research value and application prospect in the non-destructive stress detection of oil and gas pipelines.

In recent years, scholars at home and abroad have conducted in-depth research on the possibility of quantitative evaluation of stress detection of ferromagnetic materials by using magnetic property detection technology. Wang et al. [11] proposed a magnetic mechanics model of permeability and stress difference based on the relationship between stress and permeability difference, which is the equation of the coupling relationship between stress and magnetic field of ferromagnetic materials. Liu et al. [12] used the finite element method to analyze the static and mechanical properties of ferromagnetic samples, and simulated the variation law of residual magnetic signal in the stress concentration area. Zhang et al. [13] proposed a non-contact stress detection scheme based on magnetoelastic effect and established a theoretical model of transmission stress detection. Zeng Weijie et al. [14] designed a principle verification test system based on the inverse magnetostriction effect for the on-line detection of the internal stress of steel plate, developed an excitation module for on-line dynamic detection and a fast signal processing system, and verified the feasibility of on-line magnetic measurement for the internal stress of steel strip through experimental research. Zhouming et al. [15] proposed a steel stress detection method based on magnetoelastic effect under the condition of weak AC magnetization, and studied the approximate linear monotonic relationship between the amplitude of normal weak AC induced magnetic field and stress on the surface of steel plate. The above research results are based on qualitative research and are not yet mature. The technology of magnetic stress measurement needs further research.

There are two main methods to detect the reverse magnetostriction effect based on ferromagnetic materials, metal magnetic memory detection method and magnetic anisotropy detection method. However, due to the relatively weak magnetic memory signal, the actually detected signal is vulnerable to interference from the external environment, and

Based on the inverse magnetostriction effect, a stress detection model of inverse magnetostriction effect is established by using COMSOL finite element software, and the relationship between the complex stress changes in the straight pipe section of pipeline transportation and the magnetic induction intensity output of coil probe is numerically simulated. Verify the corresponding relationship between the stress change of ferromagnetic materials and the output electromagnetic signal of the four pole probe. The influence factors of the pipeline inner wall loading stress on the sensor output electromagnetic signal are studied, and the electromagnetic signal corresponding to the pipeline wall stress with missing filling is analyzed to judge the feasibility of the detection method.

2. Theoretical Model of Stress Detection for Inverse Magnetostriction Effect

2.1. Inverse magnetostrictive effect of ferromagnetic materials

The phenomenon that the size and volume of ferromagnetic materials change under the magnetization of an external magnetic field is called magnetostriction effect [16]. Contrary to the magnetostrictive effect, the phenomenon that ferromagnetic materials deform under the action of external forces such as pressure, tension and torsion, resulting in the change of magnetic induction intensity is called inverse magnetostrictive effect [17]. That is, the ferromagnetic material causes the change of permeability or magnetoresistance under the action of external force. Under the condition of providing a constant magnetomotive force to the induction coil of the anisotropic sensor, this sensor can just detect the change of the induced electromotive force induced in the ferromagnetic material, so as to convert the non electrical stress or strain into an easily measured electrical quantity, so as to achieve the purpose of stress detection [18]. This is the basic principle of stress measurement using inverse magnetostriction effect, and its transformation process is shown in Figure 1. This paper mainly studies the relationship between the output electromagnetic signal and different stress loads.

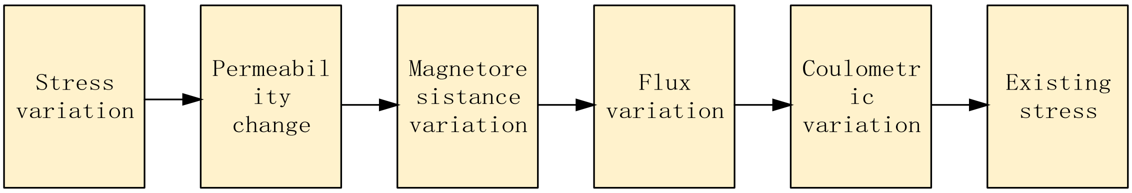

Figure 1. Schematic diagram of reverse magnetostriction effect detection

2.2. Magneto mechanical model analysis of ferromagnetic materials

Under the action of excitation magnetic field and external stress, the magnetization of ferromagnetic materials is mainly affected by the external magnetic field energy EH and stress Eσ energy. Then the energy E relationship of the material along the reversible non hysteresis magnetization curve is

$$E = E_H + E_\sigma = \mu_0 HM + \frac{3}{2}\sigma\lambda \tag{1}$$

In formula (1): μ0 is the permeability in vacuum; H is the applied magnetic field strength; M is the magnetization without stress; σ is the stress; λ is the magnetostriction coefficient.

According to the J-A theoretical model [19], the relationship between the magnetostriction coefficient and magnetization of the material can be expressed as

$$\lambda = \sum_{i=1}^{\infty} \gamma_i M^{2i} \tag{2}$$

In equation (2), γ_i is the material correlation coefficient. For general ferromagnetic materials, let i=2 to obtain the approximate expression of magnetostriction coefficient as:

$$\lambda \approx \gamma_1 M^2 + \gamma_1 M^4 \tag{3}$$

The effective field He can be expressed as the derivative of energy versus magnetization m, and its expression is

$$H_e = \frac{1}{\mu_0}\frac{dE}{dM} = H + \frac{3\sigma}{2\mu_0}\left[2\gamma_1 M + 4\gamma_2 M^3\right] \tag{5}$$

It can be seen from the above formula that the effective field is linearly correlated with magnetization and stress. When the external magnetic field is constant, the effective field changes with the change of stress.

Under the action of external magnetic field and stress, the magnetization without hysteresis can be expressed as a function of effective magnetic field

$$M(H,\sigma)=M_s[\coth(\frac{H_e}{a})-\frac{a}{H_e}] \tag{6}$$

Where MS is the saturation magnetization; a is the material constant.

The relationship between magnetization and relative permeability μ r of ferromagnetic materials is

$$M=\left(\mu_r-1\right)H \tag{7}$$

The magnetic permeability under the action of magnetic field strength and stress is

$$\mu_r=M_s[\coth(\frac{H+\frac{3\sigma}{2\mu_0}(2\gamma_1 M+4\gamma_2 M^3)}{a})-\frac{a}{H+\frac{3\sigma}{2\mu_0}(2\gamma_1 M+4\gamma_2 M^3)}]\frac{1}{H+1} \tag{8}$$

It can be seen from equation (8) that the stress of the material is positively correlated with the permeability of the material under the joint action of the external magnetic field and stress when the external magnetic field and the relevant parameters of the material remain unchanged.

2.3. Measurement principle of pipeline electromagnetic stress detection system

Due to the complex stress of the pipeline in the external environment, the permeability in the pipeline changes with the change of stress. In order to monitor the stress change of each point in the oil and gas pipeline, a four pole sensor is designed according to the law of electromagnetic induction, as shown in Figure 3., The probe is self-excited and self generating. After sinusoidal alternating current is applied to the probe coil, an alternating electromagnetic field is generated. A circular eddy current centered on the central axis of the probe coil and related to the permeability distribution of the pipe is generated on the inner wall of the pipe. The eddy current forms a secondary alternating electromagnetic field. The change of magnetic flux detected by the self-excited and self sensing probe is related to the permeability of the pipe near the probe and the stress distribution of the pipe wall near the probe. The stress detection principle of induction probe is shown in Figure 3.

An alternating magnetic field is generated on the induction coil wound around the probe and magnetic core, and the change of the magnetic field is corresponding to the change under stress. If the inner wall of the pipe is in a stress-free state, because the ferromagnetic material is isotropic, the measuring coil is in a stable magnetic potential line, and the magnetic flux in the measuring coil is constant. When there is a stress acting on the measured material, the relative permeability of the surface of the measured material changes due to the change of the magnetization state, and the magnetic flux of the measuring coil changes. The stress of the inner wall of the pipe is deduced by the change of the probe magnetic flux.

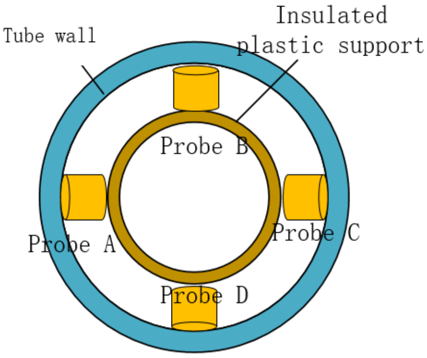

Figure 1. Four pole sensor

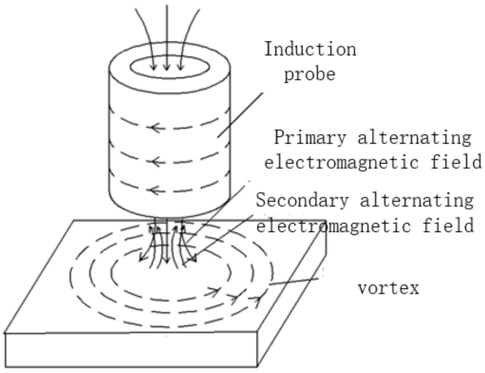

Figure 2. Schematic diagram of stress detection principle of induction probe

Through the magnetic sensor to obtain the magnetic field change signal at the stress of the pipe, the excitation coil will generate an alternating electromagnetic field under the excitation of the sinusoidal signal. The magnetic field will pass through the pipe wall, and the electromagnetic signal will be generated at the stress concentration, which will change the magnetic induction intensity of the coil, thus causing the change of the magnetic flux of the coil. Assume that the alternating magnetic field generated by the probe coil is

$$H = H_0 \sin(\omega t) \tag{9}$$

Where H_0 is the peak value of sinusoidal alternating magnetic field; ω is the alternating angular frequency of the applied magnetic field; t is the time.

The magnetic flux of the probe coil is

$$\Phi = NS\mu_r H \tag{10}$$

Where Φ is the magnetic flux of the coil and N is the number of turns of the sensor coil; S is the core area; μ_r is the effective permeability.

When sinusoidal alternating current is applied to the induction probe, the frequency should be controlled in an appropriate range. According to the skin effect theorem, the detection depth will increase with the increase of excitation frequency. The expression of skin effect is

$$h = \sqrt{\frac{2}{\xi \mu f}} \tag{11}$$

Where: h is the detection depth, μ is the material permeability; ξ is the conductivity of the material; f is AC excitation frequency.

When the excitation frequency is too high, the measurement depth of the probe will be shallow due to the skin effect, and the effect of stress change in the pipeline is not obvious; The signal generated by the frequency over bottom probe is weak and vulnerable to external interference. According to the thickness of the oil transportation pipeline, the excitation frequency of the general control probe is 15~60 Hz, which can get a better electromagnetic signal.

3. Numerical Simulation of Pipeline Stress Detection and Selection of Measurement Points

3.1. Verification of theoretical model for pipeline stress detection

In order to further verify the correctness of the theoretical model of the system, the corresponding relationship between pipe wall stress and permeability is studied. Therefore, to simulate the change of magnetic induction intensity around the pipe wall within the range of permeability, this analysis method can not reveal the influence of relative permeability change on the magnetic field in the pipe, but can only be solved by numerical solution. When the relative permeability distribution of the pipe wall is not uniform, the finite element method can effectively solve the electromagnetic field distribution in the pipe.

COMSOL simulation software was used to simulate the change of relative permeability of the whole tube wall and the change of magnetic induction intensity in the probe. The results show that the magnetic induction intensity increases with the increase of the relative permeability of the tube wall. In fact, when the oil pipeline wall is subjected to an external force, the relative permeability of the entire pipe wall does not change, but only in the strong acting area. Therefore, simulate the influence of the change of relative permeability of the pipe under the action of tensile stress on the output magnetic induction value of probe a, and verify the change process of the relative permeability of the pipe wall with the gradual increase of tensile stress. The geometric mesh generation model is shown in Figure 2.

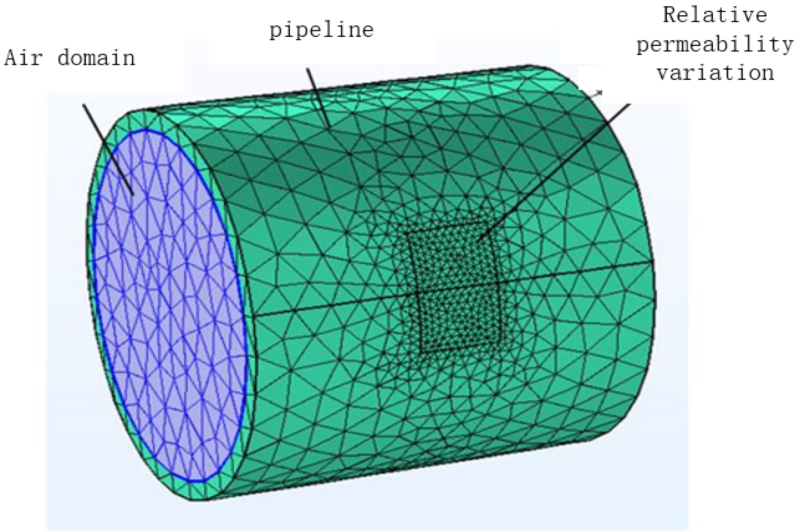

Figure 3. Meshing of the relative permeability anomaly model

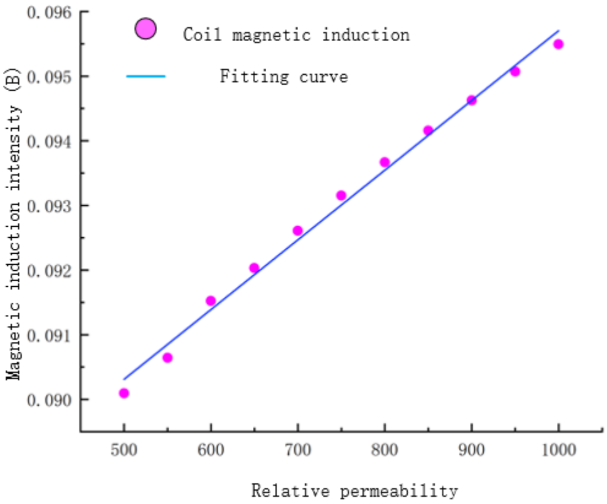

Figure 4. Relationship between magnetic induction intensity of probe and relative permeability of pipeline

The pipeline material is stainless steel. The variation range of the relative permeability of the oil pipeline wall is generally 500-1000. Set the sinusoidal alternating current acting on probe a as 30a, and the number of turns of the probe coil as 500. The relationship between the corresponding output magnetic induction value of probe a within the variation range of the relative permeability is calculated as shown in Figure 3.

It can be seen from the figure that there is a linear positive correlation between the magnetic induction intensity and the relative permeability. By changing the overall magnetic performance of the pipe wall, the fitting equation is y=0.085+1.078x, which is consistent with the theoretical results derived above.

3.2. Selection of measurement points for pipeline stress detection

As the measuring coil is affected by the skin effect, the distance between the coil and the pipe wall needs to reach an appropriate distance. For this, take probe a as the simulation object, and set 6 measuring points, as shown in Figure 5.

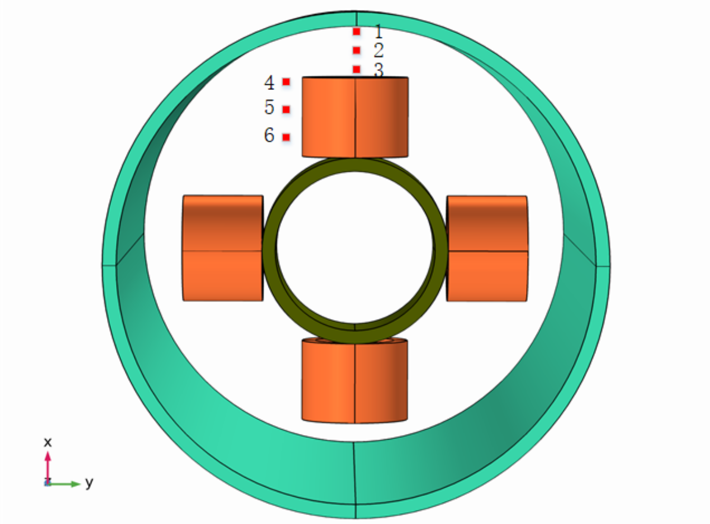

Figure 5. Selection of measurement points for pipe coil probe

It can be seen from the magnetoelastic effect that when the stress of ferromagnetic material changes, its internal permeability will show a special change rule with the stress. Therefore, the process of the permeability change after the pipeline is stressed is simulated, and the change results of the amplitude BZ of the normal magnetic field intensity at six measuring points with the permeability are obtained, as shown in Figure 6.

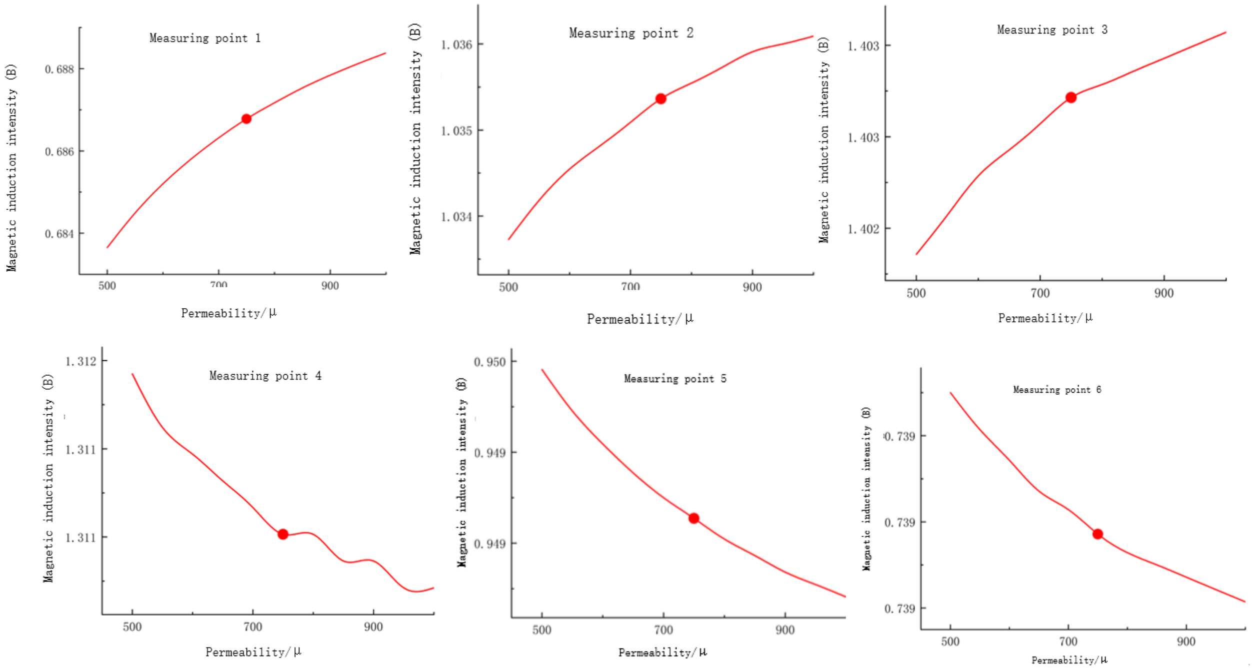

Figure 6. Variation curve of BZ at different measuring points with μ

It can be seen from the figure that there is a monotonous change relationship between the magnetic induction intensity of measuring points 1-6 and the relative magnetic conductivity from the tube to the inner wall. For measuring points 1-3, BZ is positively correlated with μ, and for measuring points 4-6, BZ is negatively correlated with μ. Measurement point 1 is far away from the coil and closest to the tube wall. At this time, compared with other measurement points, BZ here is the smallest and BZ sensitivity with μ is the largest. Therefore, the coil position is set at the measuring point 1 in the subsequent simulation experiment, which can better study the magneto-mechanical sensitive characteristics of the inner wall of the pipeline.

4. Simulation Experiment and Analysis of Pipeline Stress

On the basis of the numerical experiment, the magnetic experiment of the pipe wall under external force is carried out. The relative permeability of the pipe changes with the change of stress. When under tensile stress, the relative permeability gradually increases with the increase of tensile stress. When under compressive stress, the relative permeability gradually decreases with the increase of compressive stress. The stress applied by the simulation is within the range of elastic deformation. Using three-point bending load

The size of the geometric model of the pipeline is set as follows: the outer diameter is 5cm, the inner diameter is 4.5cm, the wall thickness is 0.5cm, the length is 10cm, the material is stainless steel, the conductivity is 1.937s/m, the relative permeability is 600, the density is 7080kg/m3, the young's modulus is 0.254pa, and the Poisson's ratio is 2.0710. Solid mechanics and electromagnetic field are selected to add physical field, and the loading stress load is 0-50kn.

4.1. Relationship between electromagnetic signal and loading stress

A three-point bending load simulation experiment is applied to the pipe wall model. Under the force, the stress changes of each point in the pipe wall are calculated through the experiment, which can verify the effectiveness of the electromagnetic method for detecting the stress in the inner wall of the pipe. The stress position of three-point bending is shown in Figure 7. During the simulation, an external force of the same size is applied at the midpoint of the short pipe and the two points 3cm away from the pipe end, and fixed constraints are set at the pipe end boundary. The stress distribution of the pipe is calculated as shown in Figure 8.

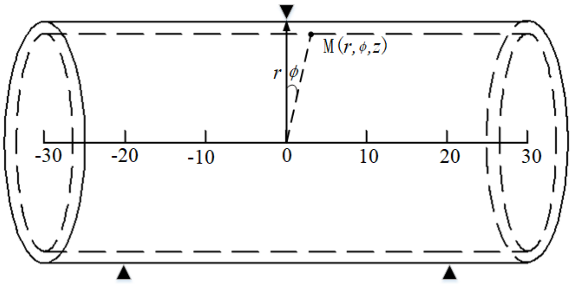

Figure 7. Three point bending load point of pipeline

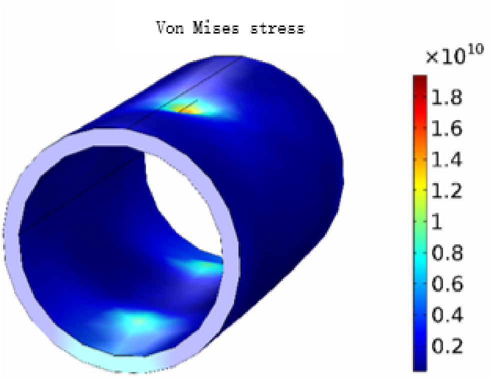

Figure 8. Cloud chart of stress distribution under three-point bending load

In order to effectively study the relationship between the excitation frequency of the coil and the external force, the excitation frequencies of 10Hz, 20Hz, 30Hz, 40Hz and 50Hz are respectively used to calculate the magnetic induction intensity relationship of the inner wall of the pipe at the center inner surface point m (0°, 0) under different external forces, as shown in Figure 9.

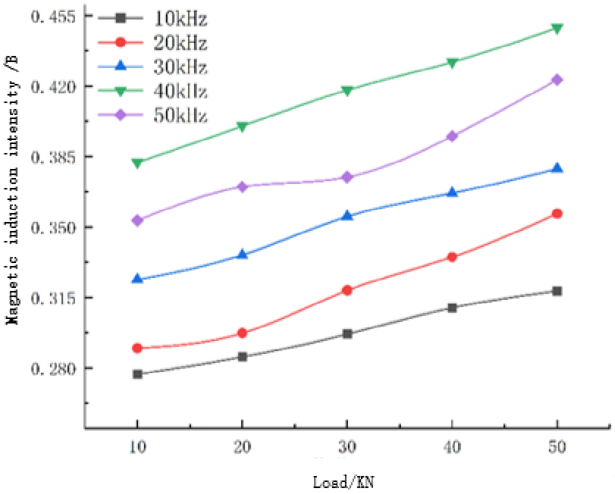

Figure 9. Relationship between magnetic induction intensity and external force at (0°, 0)

It can be seen from the figure that the electromagnetic signal at (0°, 0) inside the pipe wall gradually increases with the increase of the applied load, and reaches the maximum at 40KHz, indicating that the higher the coil excitation frequency, the stronger the electromagnetic signal inside the pipe wall, and the higher the stress resolution at this point. At the same time, the relationship between electromagnetic signals with different frequencies and the corresponding load response is positively correlated. In order to obtain the optimal electromagnetic signal, the coil excitation frequency is set at 40KHz in the subsequent experiments.

4.2. Relationship between electromagnetic signal and different detection angles

Keep the position where the external force is applied unchanged, the excitation frequency of the coil is 40Hz, keep the four probe coils in the same detection section, and calculate the electromagnetic signal relationship at different angles (0°, 0), (90°, 0), (180°, 0), (270°, 0), as shown in Figure 10.

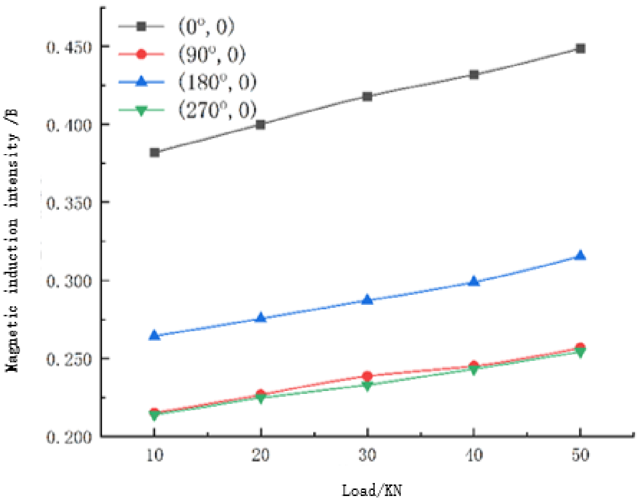

Figure 10. Relationship between magnetic induction intensity and external force at different positions

It can be seen from the figure that the magnetic induction intensity on the inner surface of the pipeline is the maximum at the point of application of external force (0°, 0), (90°, 0), (270°, 0), and the magnetic induction intensity is the minimum at the two points. With the increase of the applied load, the electromagnetic signal also gradually increases. The closer the four different measuring points are to the point of application of external force, the greater the electromagnetic signal.

4.3. Variation relationship between electromagnetic signal and different axial distances

Keep the external force unchanged (50kN), the frequency is 40KHz, the point of application of the external force unchanged, take the point of application of the force as the central measurement point, and calculate the relationship between the angular position of the symmetrical points at both ends of the axis and the change of the electromagnetic signal, as shown in Figure 11.

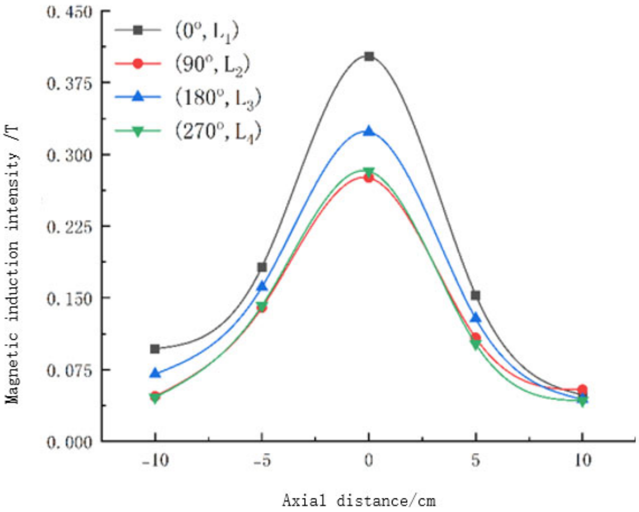

Figure 11. Relationship between axial distance at different angles and external force

Due to the complex stress of the pipeline, in order to study the relationship between the electromagnetic signal and the stress at the missing filling, a cylindrical missing filling with a radius of 0.1cm and a height of 0.5cm is set at the inner surface of the center of the three-point bend, and the relationship between the different distances of symmetrical points at both ends of the axis and the electromagnetic signal containing defects is calculated as shown in Figure 12.

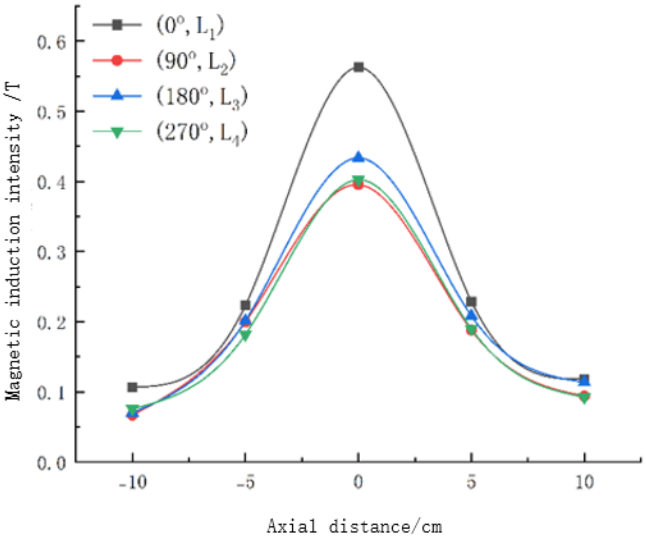

Figure 12. Relationship between axial distance at different angles and external force with missing filling

It can be seen from the figure that the electromagnetic signal containing defects is the largest at the point of stress application, and the magnetic induction intensity of the electromagnetic signal containing defects is about 36.2% higher than that of the electromagnetic signal without filling defects. Therefore, when using this method to detect the stress on the inner wall of the pipeline, when the stress concentration causes filling defects, the corresponding filling stress can be better distinguished.

5. Conclusion

(1) In this paper, a method of measuring pipeline stress based on inverse magnetostriction principle is used to derive the relationship between stress and relative permeability of material, and then verified by finite element simulation. The optimal magnetic force sensitive characteristics of coil and tube wall are obtained.

(2) The simulation experiment using three-point bending load shows that with the increase of load, the magnetic induction intensity of the inner wall of the pipeline increases, and the magnetic induction intensity is linear with the change of external force.

(3) The electromagnetic signal with higher excitation frequency has higher resolution to the force, and the frequency of 40KHz is the best excitation frequency of the coil.

(4) The stress variation trend of the simulation experiment is consistent with that of the numerical simulation, and the load and loading frequency are consistent. The electromagnetic signal with missing filling is 36.2% higher than that without defects.

(5) It is effective and feasible to use the principle of inverse magnetostriction to detect pipeline stress. By using this stress detection method, the concentrated stress on the inner wall of the pipeline can be monitored, and the pipeline damage caused by stress concentration can be better and effectively prevented.

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