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RESEARCH ARTICLE

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FINITE ELEMENT SIMULATION OF DC LEAKAGE MAGNETIC FIELD DISTRIBUTION BASED ON WIRE ROPE DEFECT DETECTION

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ABSTRACT

Wire rope detection involves the development of the national economy and the safety of people's lives, and its accuracy mainly depends on the quality and sensitivity of the sensor. Through Maxwell finite element analysis software, the distribution of leakage magnetic field signal is simulated and analyzed. The law of the distribution of the leakage magnetic field above the defect is studied, the influence of the length and depth of the defect on the distribution of the leakage magnetic field above the defect, the lift-off height of the yoke, the structure size of the ferrite, and the relative permeability of the ferrite are studied. According to the law of the leakage magnetic field, and the relevant parameters and the leakage magnetic field are fitted into mathematical formulas through matlab, some meaningful research results are obtained. This research conclusion can provide a reference for the design and development of high-sensitivity detection sensor structure.

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INTRODUCTION

With the rapid development of social economy and the rapid advancement of technology, my country's demand for steel wire ropes in the industrial field is increasing, and the use of steel wire ropes is also expanding (1,2).Nowadays, steel wire ropes are widely used in metallurgy, construction, mining, tourism, ports, transportation, petroleum exploration, and military industry (3), and their use range is very wide, depending on the special structure of the steel wire rope. Its advantages are very prominent. It has light weight, good elasticity, high tensile strength and fatigue resistance (4), and very stable working performance. It is a key link to ensure the safety of industrial production and equipment operation (5).Due to the harsh environment of use of wire ropes, problems such as wire breakage, abrasion, corrosion, fatigue, etc. may occur during the use of wire ropes. Therefore, it is necessary to develop corresponding wire rope defect detection instruments. In the process of making steel wire rope testing physical instruments, many external factors need to be considered, including the selection of excitation device, the establishment of excitation structure, the height of magnetic sensor placement, etc. These factors can be simulated well by using finite element simulation software, and the production of physical instruments can be guided through these simulation data. Ren Mingyue et al. used the DC magnetic flux leakage detection method based on the excitation coil, and found that more than 3 excitation coils can magnetize the mining wire rope to saturation through the simulation analysis of the magnetic field of multiple coils arranged in the circumferential direction of the mining wire rope (6);Zhu Weijie and others found that the use of coaxial magnetization can improve the magnetization effect of the wire rope, reduce the contact with the excitation detection device, and reduce the weight

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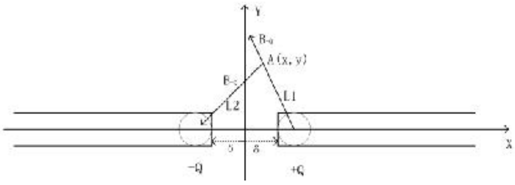
of the excitation detection device (7); Hu Xiaoqi adopts the active DC excitation method, the Hall element as the detection device, and the principle of magnetic flux leakage detection. Determine the position of broken wires and determine the number of broken wires by detecting the change of leakage flux, and use assembly language to design the software of the lower computer (8).

Theoretical basis of model simulation of steel wire rope leakage magnetic field: Detecting the magnetic flux leakage signal can be done through the attribute judgment analysis of the characteristics of the magnetic flux leakage signal (9),Through the use of the magnetic dipole model to analyze different types of damage of the steel wire rope (10), the magnetic dipole model is shown in Fig. 1:



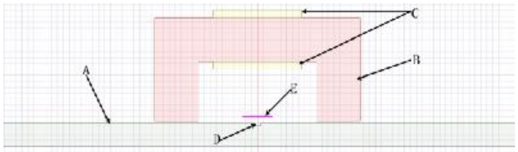


Fig.1 Schematic diagram of the magnetic dipole modelFig. 2 Simulation model

In Fig. 1, positive and negative Q are a pair of magnetic dipoles, Q is its magnetic charge, L1, L2 are the distance from the magnetic charge to point A, and B is the direction and size of the magnetic field of the two magnetic charges at A; The Y axis is the lift-off direction; the magnetic induction magnitude of +Q, -Q at point A is calculated as

$$B_{+Q} = +\frac{QL_1}{4\pi\mu_0 L_1^3} \tag{1}$$

$$B_{-Q} = -\frac{QL_2}{4\pi\mu_0 L_2^3} \tag{2}$$

In the formula, $\mu_0 = 4\pi \times 10^{-7} H/m$ is the vacuum permeability.

The horizontal component of the magnetic dipole at point A:

$$B_{+Q_1} = +\frac{QL_1}{4\pi\mu_0 L_1^3}\cos\alpha \tag{3}$$

$$B_{-Q_1} = -\frac{QL_2}{4\pi\mu_0 L_2^3}\cos\beta \tag{4}$$

In the formula, $\alpha, \ \beta$ is the horizontal angle of $L_1 L_2$; from this, the vertical component of point A can be obtained:

$$B_{+Q_2} = +\frac{QL_1}{4\pi\mu_0 L_1^3}\sin\alpha \tag{5}$$

$$B_{-Q_2} = -\frac{QL_2}{4\pi\mu_0 L_2^3}\sin\beta \tag{6}$$

The magnetic induction intensity at point A is:

$$B_x = B_{+Q_1} + B_{-Q_1}, \quad B_y = B_{+Q_2} + B_{-Q_2}$$

$$B_1 = \frac{Q}{4\pi\mu}\left\{\frac{x+\delta}{[y^2+(\delta+x)^2]^{\frac{3}{2}}} - \frac{x-\delta}{[y^2+(\delta-x)^2]^{\frac{3}{2}}}\right\} \tag{7}$$

$$B_2 = \frac{Q}{4\pi\mu}\left\{\frac{y}{[y^2+(\delta+x)^2]^{\frac{3}{2}}} - \frac{y}{[y^2+(\delta-x)^2]^{\frac{3}{2}}}\right\} \tag{8}$$

B_1 and B_2 are the magnitude of the leakage magnetic field of the wire rope at point A.

The influence of the change of related parameters in the wire rope simulation detection model on the distribution of the leakage magnetic field: Use Maxwell2019R3 finite element simulation software to simulate the magnetic induction distribution of the defective wire rope. The 2D module of Maxwell is used here. The overall model is shown in Fig. 2:Here, A is a steel wire rope with a diameter of 8mm and a length of 240mm. The material uses steel-1008 from the Maxwell material library, and the yoke B uses the ferrite material from the material library, with a relative permeability of 1000.Coil C is wound with copper wire, the relative permeability is 0.999991, D is a defect with a length of 2mm and a depth of 1mm. The monitoring wire E (representing a magnetic sensor, used to detect changes in the leakage magnetic field) is 10mm in length and 2mm on the surface of the wire rope, that is 6mm above the origin; The balloon boundary conditions are used, the calculation type is the eddy current method, and the DC excitation method is used.

The relationship between the leakage magnetic field and the ampere-turns of the excitation current: First carry out the simulation of the relationship between the magnitude of the excitation current and the change of the leakage magnetic field, the excitation current simulation range is set between 1000An and 10000An, each time increasing by 1000An (An is ampere-turn),the obtained results of the Bx axial component and By radial component of the defect leakage magnetic field are shown in Fig. 3.

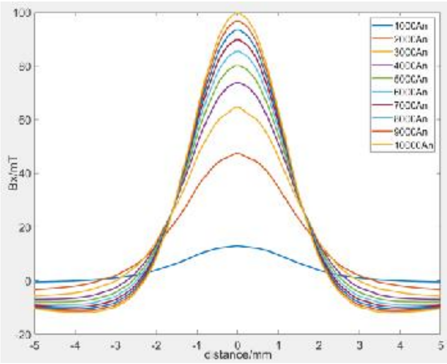


Fig.3a The distribution of the axial component leakage magnetic field under different ampere-turn current conditions

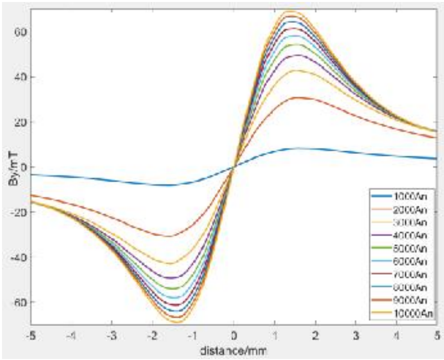


Fig.3b shows the distribution of the radial component leakage magnetic field under different ampere-turn current conditions

From the two figures in Fig.3, it can be seen that with the increase of the excitation current, the change of the magnetic field at the defect presents a trend of first sharp increase and then gentle increase. After 6000An, the growth trend increases in direct proportion, so 6000An is selected as the excitation current for the next simulation.

The distribution law of the leakage magnetic field with the height from the surface of the wire rope: Simulate the relationship between the lift-off of the monitoring line (representing the magnetic sensor) and the change of the leakage magnetic field. The lift-off height range is 2mm-16mm, increasing by 2 mm each time, and the results of the Bx axial component and By radial component of the leakage magnetic field of the defect are shown in Fig. 4.

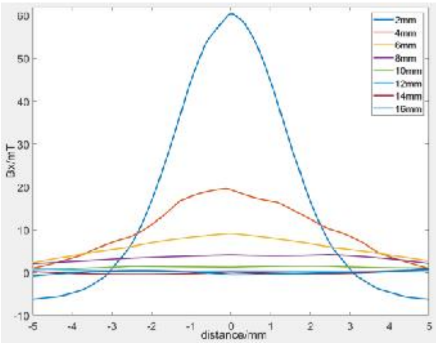


Fig.4a Distribution of axial component leakage magnetic field at different lift-off heights

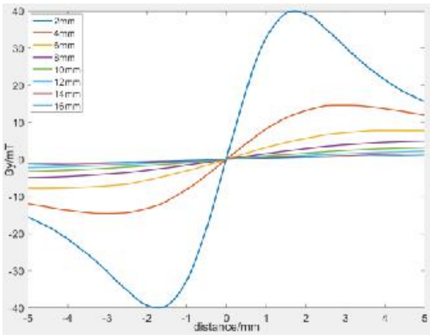


Fig.4b The distribution of the leakage magnetic field of the radial component under different lift-off heights

It can be seen from the difference between the peak and trough of the radial component leakage magnetic field in Fig.4b that the farther away from the defect, the smaller the difference, and the smoother the fluctuation of the leakage magnetic field; It can also be seen from the change of the axial component leakage magnetic field in Fig.4a that as the height of the monitoring line increases, the peak of the leakage magnetic field at the defect becomes smaller and the change trend gradually becomes smaller. Among them, the change is relatively fast between 2mm and 10mm, and then the change is relatively smooth. Through the basic fitting method of matlab, the fitting relationship of the Bx axial component curve can be obtained as$y=-0.0012x^5+0.066x^4-1.4x^3+14x^2-72x+160$,The change curve of By axial component can be fitted as the equation is $y=-0.0019x^5+0.098x^4-2x^3+20x^2-100x+210$. Through the analysis of the distribution law of the leakage magnetic field with the height from the surface of the wire rope, it is shown that the monitoring line (sensor) is as close as possible to the defect in order to obtain a larger defect signal.

The relationship between the intensity of the leakage magnetic field and the length of the crack defect: Perform a parametric scanning analysis on the defect length to study the relationship between the defect length and the corresponding magnetic field intensity.Here, the height of the inspection line is determined to be 2mm above the crack defect, that is, 6mm above the origin, and the defect depth is 1mm.The scanning range of defect length is 1 mm-8 mm, increasing by 1 mm in turn. The obtained Bx axial component and By radial component leakage magnetic field data results are shown in Fig.5: It can be seen from Fig.5 that as the length of the defect increases, the peaks of the Bx axial component curves first increase and then decrease, and the distance between the two troughs is gradually increasing; Through the radial component of By, it can be seen that as the length of the defect increases, the difference between the peak and the trough in the X-axis direction and the Y-axis direction is gradually increasing.

From the two figures in Fig.5, it can be seen that as the length of the defect increases, the peak value of each curve of the Bx axial component is a trend that first increases and then decreases, and the distance between the two troughs is gradually increasing; Through the radial component of By, it can be seen that as the length of the defect increases, the difference between the peak and the trough in the X-axis direction and the Y-axis direction is gradually increasing.

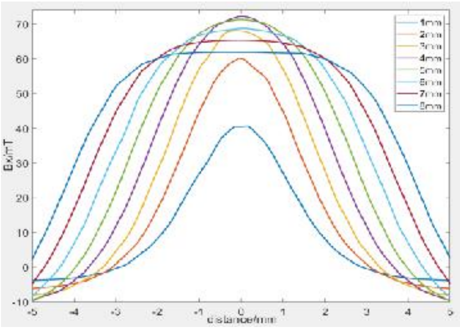


Fig.5a The distribution of the axial component leakage magnetic field of different defect lengths

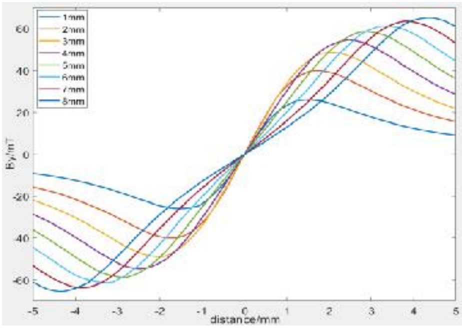


Fig.5b The distribution of the leakage magnetic field of the radial component of different defect lengths

It can be seen from the axial component of Bx in Fig.5a that the magnetic field Bx first increases and then decreases with the increase of the defect length l, which belongs to a parabolic trajectory. Through fitting, the change law of the axial component of Bx can be obtained. The approximate equation is $Bx=-0.033l^4+0.91l^3-9.5l^2+42l+7.6$;From the distribution law of the radial component of By in Fig.5b, it can be seen that as the length of the defect increases, the difference ΔBy between the peak and the valley gradually increases. Through fitting, the change equation of the difference between the wave peak and the wave trough with the crack length l can be obtained as $\Delta By=-0.031l^4+0.86l^3-9.2l^2+50l+11$.It can be seen from Fig.5a that there are two solutions for the same Bx value. In actual inspection, it is difficult to judge the length of the defect if such a situation is encountered, and the radial component trajectory of Fig.5b has no such problem. Therefore, the length of the defect can be accurately judged through the use of two equations in actual inspection. Through the simulation study of the relationship between the leakage field strength and the length of the crack defect, it is found that, the difference between the peak-to-peak position and the peak-to-peak value of the detection signal By can reflect the information of the crack length; The peak signal of the detection signal Bx above the defect is a two-valued function of the defect length, and the difference between the positions of the two minimum values of Bx can reflect the information of the crack length. The simulation results can provide a reference for the quantification of crack length.

The relationship between the intensity of the leakage magnetic field and the depth of the crack defect: Perform a parameterized scan on the depth of the defect to analyze the relationship between the depth of the defect and its corresponding magnetic field strength. The scanning range is 1mm-8mm, increasing by 1mm in turn, here only the defect depth is changed and the remaining conditions remain unchanged. The results of the axial component of Bx and the radial component of By are shown in Fig.6: It can be seen from the two figures in Fig.6 that when the defect length is constant, the greater the defect depth, the greater the difference between the peak and the valley of the Bx axial component and the By radial component; The X-axis difference at the two turning points of the Bx axial component and the difference between the peak and trough of the By radial component in the X-axis direction are close to a fixed value, and this fixed value is the defect length. It can be seen from the two graphs in Fig.6 that as the depth of the defect increases, the peak change of the Bx axial component and the difference between the peak and trough of the radial component of By are gradually increasing. Through fitting, the relationship between the peak of the axial component of Bx and the crack depth h can be obtained as$Bx=0.0081h^5-0.16h^4+1.2h^3-7.2h^2+72h-5.4$.The relationship between the peak and trough difference of By radial component ΔBy with crack depth h can be obtained as $\Delta By=-0.0023h^4+0.35h^3-7.6h^2+96h-8.6$.

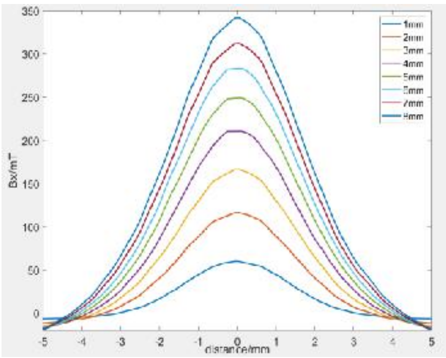


Fig.6a Variation distribution of the axial component leakage magnetic field at different defect depths

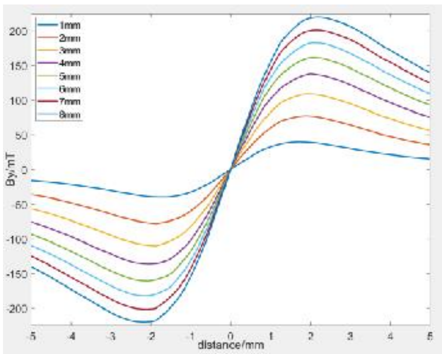


Fig.6b The distribution of the leakage field length of the radial component of different defect depths

Detect the influence of the lift-off fluctuation of the magnetic yoke on the leakage magnetic field: The lift-off parameterized scan is performed on the yoke, and the relationship between the lift-off fluctuation of the yoke and the corresponding magnetic field intensity is analyzed. In the process of physical inspection, in order to enhance the inspection effect, make the inspection probe close to the surface of the wire rope. Therefore, there is generally no large fluctuations in the detection process, so the scanning range is set to 0mm-2mm (here 0 mm means that the yoke is 0.5 mm above the wire rope) and increase by 0.4 mm, the other conditions remain unchanged, and the result of the Bx axial component is shown in Fig.7: It can be seen from Fig.7 that as the lift-off height of the yoke increases, the peak change of the Bx axial component will increase in the opposite direction. That is, when the yoke fluctuates, the value of the reduced leakage field detected by the magnetic field at the defect will increase relative to the non-fluctuation position, and the error of the detected result will increase accordingly. Therefore, when conducting physical wire rope inspection experiments, because the wire rope is wound, and the surface of the wire rope is rusty, the surface is not smooth. Then there will be a certain amount of jitter during the monitoring process, and the impact of the jitter of the detection probe on the test results should be considered when conducting wire rope testing experiments.

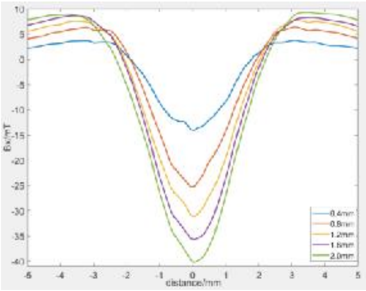


Fig. 7 The variation of the Bx axial component leakage magnetic field of the yoke with different lift-off heights directly above the defect

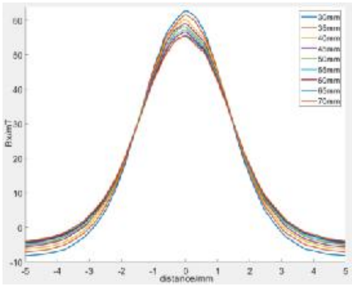


Fig.8a The variation of the leakage magnetic field of the Bx axial component of different yoke inner lengths

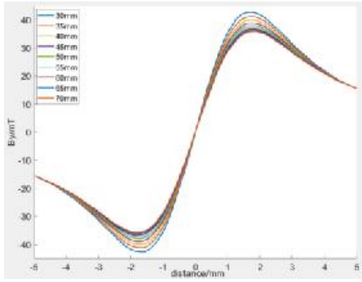


Fig.8b The variation of the leakage magnetic field of the radial component of the inner length By of different yokes

The influence of the structure size and relative permeability of ferrite on the leakage magnetic field: The simulation analysis of the shape change of the ferrite itself, such as the inner length, inner width and relative permeability of the ferrite, is related to the change of the corresponding leakage magnetic field. First, perform a parametric scan on the inner width of the ferrite, and the scan range 0mm-25mm is increased by 5mm each time (here refers to the additional width added to the original width of 20mm).Through the analysis of the simulation results of the variation of the inner width, it is found that when the inner width of the ferrite is scanned by the width increase parameter. The corresponding change in leakage magnetic field is very small and hardly affects the change in leakage magnetic field. A parametric scan is performed on the inner length of the yoke, and the scan range is 30 mm-70 mm, with an increase of 5 mm each time, and the obtained Bx axial component and By radial component are shown in Fig.8.It can be seen from the two figures in Fig. 8 that when the inner length of the ferrite is scanned for parameterization, the larger the inner length, the smaller the leakage magnetic field. The change equation of the peak of the axial component of Bx along with the inner length of the yoke b can be obtained by fitting: $Bx=0.000023b^3-0.0015b^2-0.21b+70$.The relationship equation of the difference between the peak and trough of the radial component ΔBy and the inner length b of the yoke is $\Delta By=-0.000072b^3+0.017b^2-1.5b+120$. When the relationship between the change of relative permeability and the change of the corresponding leakage magnetic field is simulated and analyzed, the change range of relative permeability is set to 500-10500.Through the simulation results, it is found that with the increase of the magnetic permeability of the ferrite, the leakage magnetic field at the defect changes little, and the change trend is a sharp increase first and then gradually smooth. When the magnetic permeability of ferrite reaches 6500, it is close to the maximum value at this time. The research results provide a basis for the material selection of ferrite.

Conclusion

Through the Maxwell finite element analysis software, the distribution of the leakage magnetic field signal is simulated and analyzed. Study the law of the leakage magnetic field above the defect. Study the influence of the length and depth of the defect on the distribution of the leakage magnetic field above the defect. Study the lift-off height of the yoke, the structure size of the ferrite, and the law of the relative permeability of the ferrite and the leakage magnetic field. The specific research conclusions are as follows:

- Through the analysis of the distribution law of the leakage magnetic field with the height from the surface of the wire rope, the sensor position is as close as possible to the defect to get a larger defect signal, and the By signal of the leakage magnetic field is greater than the Bx signal.
- Through the simulation study of the relationship between the strength of the leakage magnetic field and the length of the crack defect, it is found that the difference between the peak-to-peak position and the peak-to-peak value of the detection signal By can reflect the information of the crack length. The peak signal of the detection signal Bx is a two-valued function of the defect length, and the difference between the positions of the two minimum values of Bx can reflect the information of the crack length. The simulation results can provide a reference for the quantification of crack length.
- Through the simulation study of the relationship between the leakage magnetic field strength and the crack depth, it is found that as the depth of the defect increases, the Bx axial component peak change and the By radial component peak and trough difference are gradually increasing. Based on this information, the depth of the crack can be judged.

- Through simulation analysis to detect the influence of the lift-off fluctuation of the yoke on the leakage magnetic field, it is found that the detection signal decreases with the increase of the lift-off height of the yoke.When conducting actual wire rope testing, it is necessary to consider eliminating the influence of fluctuations on the testing results.
- The change of the inner length of the ferrite structure has little effect on the detection signal.When the inner width changes, as the inner width increases, the leakage magnetic field at the defect will decrease accordingly.
- When the relative permeability of ferrite is 500-10500, the leakage magnetic field changes small but more obvious. When it is greater than 6,500, the leakage magnetic field at the defect is close to a fixed value.

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