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TOWER CRANE WIRE ROPE DEFECT DETECTION TECHNOLOGY BASED ON MAGNETIC FLUX LEAKAGE DETECTION(MFLD)

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Abstract: This paper focuses on the damage detection system for wire ropes under the excitation of annular permanent magnets, and on this basis, conducts structural optimization and simulation research of the wire rope damage detection system. To enhance the strength of the detection signal and extend the service life of the detection unit, the positioning of the detection unit is arranged in such a way that it is not damaged by vibration or proximity, thereby ensuring the stability of the detection effect. Based on Comsol, the role of this method in excitation characteristics and magnetic flux leakage detection is studied. Furthermore, the optimized equipment is tested using numerical simulation methods to ensure that it not only meets the excitation characteristics for defects but also guarantees the extraction of magnetic flux leakage signals from the defective areas, achieving higher reliability. The research findings of this study can provide a theoretical basis for the optimal design of damage monitoring equipment for wire ropes in lifting machinery and have significant guiding importance for improving the overall performance of lifting machinery and equipment.
Keywords: Tower crane; Communication; Magnetic Flux Leakage Detection (MFLD); Wire rope defect detection

1 INTRODUCTION

Tower cranes, as pivotal equipment in modern construction, have safety and reliability that directly impact project timelines, personnel lives, and the safety of the surrounding environment. As a critical load-bearing component of cranes, wire ropes undertake the essential functions of load transfer and power conversion during hoisting, with their performance status directly affecting the operational efficiency of the entire machine. However, in recent years, safety incidents caused by wire rope failures have been frequent. Accidents due to wear, breakage, or fatigue failure, such as hoisting drops and structural collapses, not only result in significant economic losses and casualties but also expose potential loopholes in construction safety management.

Research indicates that wire rope safety issues often stem from a combination of factors including design and selection deviations, complex usage environments, lagging maintenance and inspection, and human operational errors. The traditional extensive management model of manual visual inspection and periodic replacement struggles to accurately identify hidden dangers. Seeking breakthroughs in material performance optimization, the application of intelligent monitoring technology, and the standardization of full lifecycle management has become an important task in reducing the risk of tower crane accidents and promoting safety upgrades in the construction industry.

Regarding the issue of wire rope defect detection, some researchers have already achieved commendable results,Liu et al.[1]comprehensively reviewed the method of wire rope detection, sensor technology and signal processing means, summarized its application and challenges, and provided a reference for the research and practice in related fields.Dong et al.[2] Based on digital image processing, the texture characteristics of the wire rope such as smoothness and entropy are extracted, and the internal defects are detected.Zhang et al[3]used real haulage rope images of mine ropeways to test the effectiveness and advantages of the new development method.Chen et al.[4] proposed a design scheme of quantitative detection system for broken wire based on RBF neural network, aiming at the problem of low detection accuracy of traditional wire rope broken wire measurement system.Tse, P. W et al.[5]reported on the condition monitoring of the steel wire rope of the lifting elevator, which broke due to corrosion environment and fatigue. Experiments were conducted to investigate the efficiency of using magnetostriction-based UGW for rope defect detection.Mazurek, P. et al.[6] proposed a new diagnostic program for wire rope using passive magnetic method.Xia et al. propose an image segmentation algorithm based on scale morphology to eliminate the background effects of non-uniform heating and to visualize BWs.Based on the principle of magnetic flux leakage detection, this paper analyzes and discusses the defects of steel wire rope in tower crane.

2 BASIC PRINCIPLE OF MFLD

2.1 MFLD

As shown in Figure 1, magnetic leakage measurement refers to the magnetization of the measured ferromagnetic substance and the acquisition of its internal magnetic leakage information through the magnetic induction sensing of Hall sensor. If the material inside the material is continuous and uniform, the magnetic induction line will be bound inside the material, and the direction of the magnetic field is parallel to the direction of the material. When there is a defect in the medium, the magnetic flux will distort, and part of it will leak into the surface of the medium, resulting in a leakage magnetic field. By analyzing the magnetic induction intensity of the leakage field, the corresponding defect width and depth can be obtained.

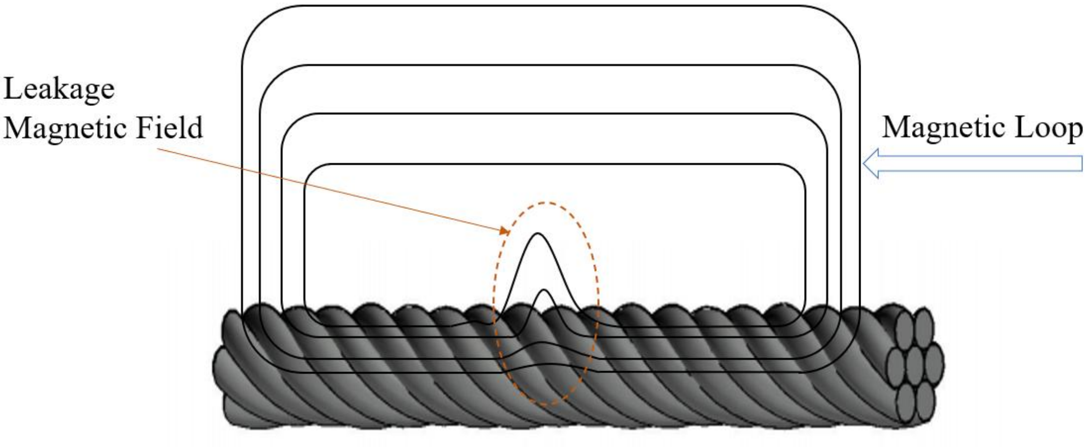

Figure 1 Principle of Magnetic Leakage of Wire Rope

By combining Maxwell equation with the interface of two different magnetic materials, the detection mechanism of magnetic leakage is explained. The leakage magnetic field conforms to Maxwell's equation:

$$\begin{cases} \oiint_{s} C \cdot dS = 0 \\ \oint_{l} \varphi \cdot dl = \sum I_1 \end{cases} \tag{1}$$

Where C is the magnetic induction intensity,φ is the magnetic field intensity, and I_1 is the magnetic conduction current. According to the principle of magnetic flux continuity, the magnetic induction line in space forms a closed loop and does not disappear or appear from a single point without thin air, and the direction of the magnetic field line changes after passing through the medium interface, as shown in Figure 2.

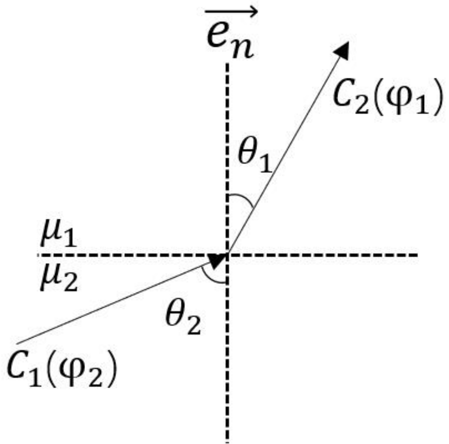

Figure 2 Magnetic Inductance Line Refraction on Different Media Surfaces

In the figure, $\overrightarrow{e_n}$ is the normal vector, μ_1 andμ_2 f are the permeability in medium 1 and medium 2 respectively, and the permeability in air is set as μ:

$$\begin{cases} C_1 = \mu_1 \mu \varphi_1 \\ C_2 = \mu_2 \mu \varphi_2 \end{cases} \tag{2}$$

Where θ_1 and rθ_2 are the angles between φ_1 and φ_2 and the normal vector of the interface respectively. I_1=0 and formula (1):

$$\begin{cases} \overrightarrow{e_n} \cdot (C_2 - C_1) = 0 \\ \overrightarrow{e_n} \cdot (\varphi_2 - \varphi_1) = 0 \end{cases} \tag{3}$$

Where, φ_1 and φ_2 are the magnetic field intensity in different media, C_1 and C_2 are the magnetic induction intensity and magnetic field intensity in different media respectively.It is obtained by formula (1)(2):

$$\frac{\tan \theta_1}{\tan \theta_2} = \frac{\mu_1}{\mu_2} \tag{4}$$

2.2 Principle of Agglomeration

The traditional method of wire break detection is to magnetize the wire rope longitudinally. When the wire break occurs in the surface layer or inner layer, it will form an outward-dispersing leakage magnetic field. Through the detection and analysis of the leakage magnetic field, the specific location and number of broken wires can be determined. The magnetic leakage field is collected and homogenized by a magnetic concentrator, and the Hall device detection channel is introduced for testing, which has high sensitivity and high signal-to-noise ratio.

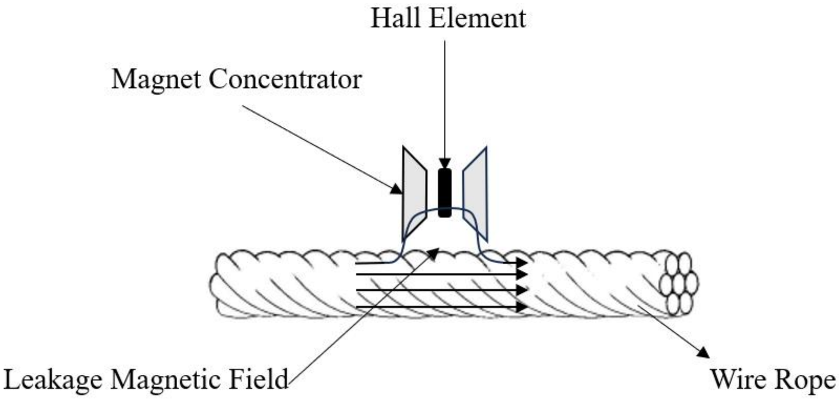

Figure 3 Detection Structure of Sensor Magnet

The structure of the magnetic flux sensor is shown in Figure 3. The leakage magnetic field is transmitted to the Hall element through the magnetic flux gathering device to form a magnetic flux gathering path, which can better gather the leakage flux to obtain more obvious magnetic flux leakage signals.

2.3 Hall Component Detection Principle

Hall sensor, an innovative sensor technology, is a magnetic detection device designed based on the Hall effect in physics. The technique utilizes the principle of electromagnetic induction by applying an electric field around a conductor, causing it to produce a change in the magnetic field, and converting this change into a measurable electrical signal. In particular, Hall sensors have demonstrated an extraordinary ability to accurately measure magnetic leakage phenomena on magnetic materials such as wire ropes.

$$U = K \cdot \frac{CI \cos \alpha}{h} \tag{5}$$

Where K is a constant and is the Hall coefficient; C is the applied magnetic induction intensity. I is the current intensity through the component; α is the Angle between the applied magnetic field direction and the element plane normal; h is the thickness of the Hall element. When K and h are constant and the external input current is constant, the Hall voltage is only related to the applied magnetic field. So the Hall element can detect the magnetic field change of the leakage field.

3 TEST DEVICE DESIGN

The simulation model of the test equipment consists of four parts: permanent magnet, armature, wire rope under test and magnetic agglomeration. In order to ensure its safe and reliable operation, the steel cables used in it require high requirements, wear resistance, and the materials are mostly carbon steel with high carbon content. The steel cable used in the simulation adopts a rod-shaped cylinder with a diameter of 26mm and a length of 220mm. The material used in the simulation is M50 steel, and there is a saturation magnetic field of about 1.9T in the steel wire rope [7].

The function of the excitation equipment is to make a saturated magnetized region appear in the detection range of the wire rope, and make it appear obvious magnetic leakage signal in the defect part. Using permanent magnet material as excitation source, N52 NdFeB with high magnetic properties is selected, which has coercivity of 1.21, 1.45 T and 955000 A/m.Both ends of the armature are equipped with annular permanent magnets, which are used to generate multi-loop excitation. The armature adopts an open ring cylinder made of industrial pure iron with high permeability.

In order to solve the problem of positioning the sensing element, the probe slot is located in the armature. In order to realize the acquisition of MFL signal and ensure that most MFL can pass through the Hall unit, a magnetic concentrator and a Hall element are placed in the central detection slot. In order to avoid noise between the wire rope strands, the axial length L of the magnet ring should be half the diameter of the wire rope.According to the diameter of the wire rope usually used in practice, L should be 10-14mm, and the axial length of the bushing should be 2mm. Therefore, when designing the location of the probe slot, the width of the probe slot is at least 38mm to ensure that the magnet can be placed. When there is a large gap between the permanent magnet, the armature and the wire rope, with the increase of the gap, the magnetic permeability will be reduced, resulting in an increase in air impedance, resulting in a decrease in the magnetic field, so that the wire rope can not be effectively magnetized.[8]On this basis, the air gap between the permanent magnet, the armature and the wire rope is set to 8 mm to meet the depth of the probe groove and the height of the lift required by the magnetic field detection equipment.

When the extraction value is smaller, the leakage magnetic field is stronger and the signal is clearer, which is beneficial to the detection of defects. However, when the extraction amount is too large, the leakage magnetic field will be significantly weakened, which will adversely affect the accuracy of the detection. Too low lifting degree will cause contact and friction between the probe and the wire rope, increase the loss of the instrument and increase the maintenance cost. In view of the steel wire rope will appear in the use of different degrees of roughness, roughness and other problems, the lifting value is increased to 4 mm, so that it has a strong adaptability, enhance the feasibility and stability of the test, and can ensure a high detection sensitivity.

On this basis, COMSOLMulti-Physics software was used to conduct finite element simulation of the wire rope damage detection system excited by the annular permanent magnet, and three-dimensional modeling was carried out, as shown in Figure. 4. Under the condition that the wire rope is not damaged, the internal magnetization of the wire rope is studied by setting a probe track in the axial direction of the wire rope. In the study of the defective leakage magnetic field, a crack of 4mm in length, width and depth is made at the zero point of the X-axis, along the axis direction of the cable axis, and a detection channel with an axial length covering the width of the detected slot is made at the position of 4.5 mm on the surface of the wire rope.

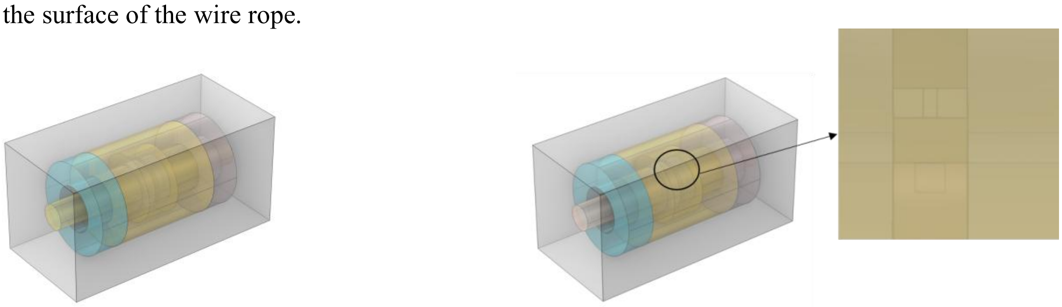

Figure 4 3D Model Diagram (a) Defect-free 3D model; (b) Defective 3D Models

4 SIMULATION ANALYSIS

Through the finite element simulation results, the key dimensions of the steel wire rope defect detection device used in this study are determined: the inner diameter of permanent magnet and armature is 24mm, the outer diameter is 72mm (the difference between the inner and outer diameters is 48mm), and the axial length of permanent magnet is 15mm. Armature axial length 80mm; The measurement slot is 15mm wide and 9mm deep. After optimization, the model formed a uniform saturated magnetic field of 1.8T on the surface of the wire rope, as shown in Figure 5. When there are defects on the surface of the steel wire rope, it can be seen from the magnetic flux density diagram of the steel wire rope with defects in Figure 6 that there is an obvious magnetic leakage phenomenon at the defect.

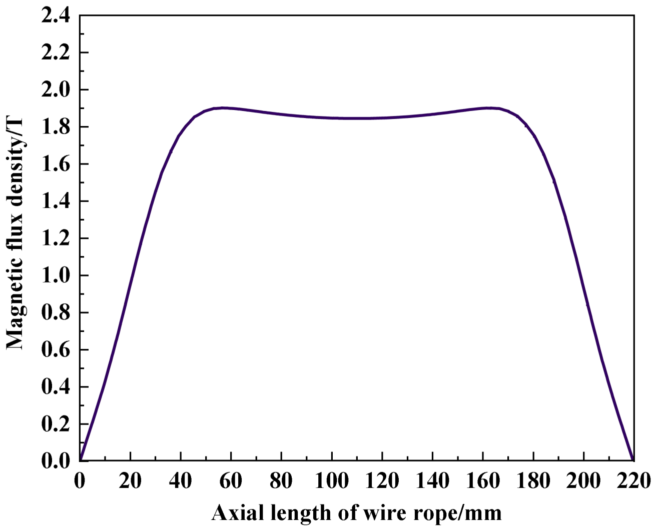

Figure 5 Schematic Diagram of Magnetic Flux Density inside the Flawless Steel Wire Rope

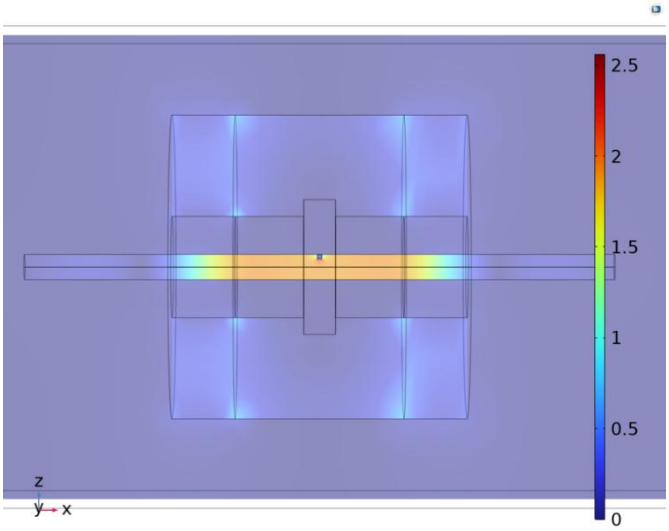

Figure 6 Magnetic Flux Density of Defective Steel Wire Rope

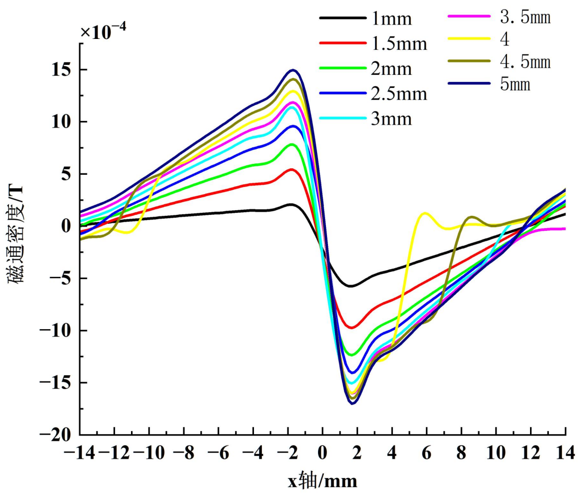

Figure 7 Peak Radial Flux Density at the Defect

As shown in Figure 7, when the lift value is 1mm, the magnetic flux density reaches the maximum value and the defect signal is the strongest. As the lift value increases to 5mm, the signal intensity decreases significantly. Considering the signal strength and the feasibility of practical application, the lift value is selected as 3mm. In addition, the 3mm lift value takes into account the mechanical tolerance in the actual installation and the possibility of wire rope vibration during the crane operation, while avoiding the excessive requirements of the 1mm lift value on the installation accuracy, achieving a cost-benefit balance.

5 CONCLUSION

In this paper, when the thickness between the permanent magnet and the armature is 25 mm, the length of the permanent magnet is 30mm, the length of the armature is 110mm, the width of the probe slot is 36mm, and the depth is 12mm, the steel wire rope can be effectively in the magnetic saturation state, ensuring that the magnetic induction intensity inside the steel wire rope is uniform without defects. Effective leakage flux density can be extracted from the surface of defective wire rope. In practical application, the magnetic concentrator can be added to the position of the detection slot to improve the detection effect and improve the detection accuracy.

Through simulation verification of the optimized device detection effect, the designed device can meet the excitation performance of defect detection, ensure that the magnetic leakage signal at the defect is detected, and realize a more reliable wire rope detection system, which provides an important reference for optimizing the wire rope defect detection device of tower cranes, and helps to further improve the performance of the detection device. It has high application value and practical significance.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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