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A Brief Discussion on the Development of Non-Destructive Testing Technology for Steel Wire Rope

Yang Gao*, Jun Yang, Baohua Qiao, Chen Qian, Qifu Zhang

Cethik Group Co., Ltd., Hangzhou 310000, Zhejiang, China

**Author to whom correspondence should be addressed.*

Abstract: In heavy-duty long-distance transmission scenarios, steel wire ropes are widely used due to their unique advantages, and their safety is very important, which has also led to the rapid development of non-destructive testing technology for steel wire ropes. The non-destructive testing technology for steel wire ropes is influenced by various factors such as its own structure and external working environment, and the testing process is relatively complex. Multiple testing methods and related types of sensors have also emerged. The electromagnetic detection method is currently the most effective method, but it also has its limitations in development and has not yet fully achieved the expected detection goals. In order to completely replace manual inspection work with the development of non-destructive testing technology for steel wire ropes, more in-depth research and long-term accumulation are still needed.

Keywords: Wire rope; Non-destructive testing; Electromagnetic detection method

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1. Introduction

As a flexible rope, steel wire rope has multiple advantages such as good flexibility, impact resistance, and tensile strength. It can achieve long-distance transmission of heavy loads and is commonly used in industries such as lifting, traction, and towing.

The working conditions of steel wire ropes are often accompanied by moisture, dust, vibration, compression, large temperature differences, etc., which can easily cause damage such as wire breakage, wear, and corrosion, affecting production efficiency and leaving hidden dangers for the safety of steel wire ropes [1]. Therefore, regular inspection and maintenance of steel wire ropes are essential. Accidents caused by steel wire rope breakage often result in varying degrees of economic losses and casualties, with a relatively negative social impact. Therefore, many countries and enterprises now attach great importance to non-destructive testing of steel wire ropes, and have formulated and introduced a series of national and industry standards, promoting the rapid development of non-destructive testing technology for steel wire ropes.

2. The complexity of non-destructive testing of steel wire ropes

Non-destructive testing of steel wire ropes is aimed at evaluating the current performance status and remaining service life of steel wire ropes, and accurately identifying, quantifying, and locating damaged areas. The complexity of non-destructive testing of steel wire ropes is mainly influenced by the following factors.

(1) Its own structure is complex: Unlike steel strands, steel pipes, etc., steel wire ropes are twisted from up to hundreds or even different diameters of thin steel wires using unique weaving techniques. Its special structure makes various detection sensors insensitive to defect results, making signal processing more difficult.

(2) There are many types of defects: There are various types and complex forms of damage to steel wire ropes, such as fatigue fracture, pitting corrosion, rusting, wire breakage, wear, etc. Each type of injury has multiple styles and influences, evolving from one injury to multiple. The detection signals of different types and degrees of steel wire rope damage are difficult to distinguish, and cannot be measured and analyzed using the same standards.

(3) The usage environment is harsh and complex: The working conditions of steel wire rope are often accompanied by severe shaking and frequent stretching. The environment is dark, humid, and the ionizing radiation of high-power equipment can have adverse effects on it. Its surface is usually covered with oil, sand, and dust, which can affect the accuracy of the detection equipment and increase the difficulty of detection.

(4) The accuracy of quantitative analysis is low: Due to the complex structure, various types of defects, and harsh and complex usage environment of steel wire ropes, the design difficulty of detection sensors has increased. The detected signals are complex and difficult to analyze, making it impossible to distinguish all types of damage and accurately calculate the degree of damage through conventional signal analysis methods. As a result, it is even more difficult to evaluate the performance and subsequent status of steel wire ropes [2].

3. Methods for non-destructive testing of steel wire ropes

Due to the fact that the earliest manual inspection of steel wire ropes could no longer meet the industry's requirements for efficiency and accuracy, various non-destructive testing technologies have been continuously developed, mainly divided into the following categories (**Table 1**).

Table 1. Comparison of main methods for non-destructive testing of steel wire rope [3,4]

Testing method	Advantages	Disadvantages
Eddy current testing method	Low cost, non-contact, and simple detection device;	Low resolution, unable to identify internal defects, difficult to conduct qualitative and quantitative analysis
Optical detection method	High cost, intuitively represent surface defects	Easy to be affected by oil pollution and dust, with high equipment costs
Acoustic detection method	Higher cost, high sensitivity, and fast detection speed	Easy to be interfered with, not easy to operate, only suitable for static testing, low signal-to-noise ratio, limited test results, and difficult defect identification.
Radiographic testing method	High cost, intuitively display defects with high accuracy	The cost of labor and protective equipment is high, harmful to human health, unable to measure continuously, and the equipment cost is high

Table 1 (Continued)

Testing method	Advantages	Disadvantages
Mechanical testing method [5]	Directly obtain the tension of the steel wire rope	Easy to be affected by impurities in the environment, not easy to operate, only suitable for static testing.
Magnetostriction detection method	Non-contact, capable of long-distance testing without the need for relative motion testing.	Has force requirements, low signal-to-noise ratio, and low quantitative detection accuracy
Electromagnetic detection method	Low cost, good environmental stability, capable of measuring internal and external defects	Difficult to conduct quantitative analysis and qualitative defect types on minor injury sites

Based on the analysis of these non-destructive testing methods for steel wire ropes in the table above, it can be concluded from multiple dimensions including operability, testing depth, advantages, and disadvantages that the electromagnetic testing method is undoubtedly the optimal choice.

4. The development status of electromagnetic detection methods

The principle of the electromagnetic detection method is divided into three parts: first, magnetizing the steel wire rope by the excitation structure; second, the leakage magnetic detection device collects leakage magnetic signals; third is to process the leakage magnetic signal through specific analysis methods to determine the current damage status of the steel wire rope.

(1) Excitation structure

The excitation structure is the primary condition for the electromagnetic detection method, and its magnetization degree on the steel wire rope has a significant impact on the signal detection results in the next step. The main goal of designing the excitation structure is to improve the signal-to-noise ratio of the magnetic leakage signal of the steel wire rope. The general excitation structure can be divided into two excitation methods: current excitation method and permanent magnet excitation method. At present, on the basis of ensuring the magnetic field strength, improving the magnetization method, magnetic circuit structure, and homogenizing the magnetization intensity are the three focuses of excitation structure design to achieve the lightweight and functionalization of the exciter. Therefore, permanent magnet excitation method is currently the main magnetization method used [4].

(2) Magnetic leakage detection device

The leakage magnetic detection device converts magnetic signals into electrical signals, which are susceptible to external interference. The accuracy and stability of signal acquisition directly affect the final detection effect. There are mainly six types of sensors for non-destructive testing of steel wire ropes (**Table 2**).

Table 2. Comparison of sensor characteristics [4]

Sensors	Advantages	Disadvantages	Application
Induction coil	Widely applicable and suitable for various working conditions	Easily affected by stock waves and noise	LF damage detection, detection range 1fT–1T
Hall sensor	Large detection range, small size, good linearity, suitable for high scanning speed	Energy consumption, easily affected by temperature	LMA damage detection, detection range 10μT–1T
Magnetoresistance sensor	High precision and high sensitivity	Small detection range, poor stability	LF and LMA damage detection, detection range 0.1nT–0.1T
Fluxgate sensor	High sensitivity and large volume	Signal complexity and energy consumption	LF and LMA damage detection
Magnetic tunnel sensor	High sensitivity, capable of detecting multiple directions simultaneously	Small linear range	10^{-10}–10^{3}T

Based on the characteristics of the six types of sensors mentioned above, Hall sensors are the most widely used in electromagnetic detection devices on the market.

(3) Leakage magnetic signal processing method

After collecting the magnetic leakage signal of the steel wire rope through sensors, defect analysis and quantitative analysis are also required. Quantitative analysis also includes defect signal extraction and quantitative calculation. From the waveform of the leakage magnetic signal collected from the steel wire rope, information such as the shape, location, and degree of damage can be obtained. The feature extraction methods mainly include the peak-to-peak exceedance method and the differential exceedance method. One method for identifying wire rope breakage signals is to establish a database based on a large number of experimental sample features, match the leakage magnetic signal with it, and thus determine the type of damage. However, due to the diverse types of damage to the steel wire rope, this method requires a large amount of work to produce samples that are close to reality and is not easy to operate, especially with internal defects. The second is to apply quantitative identification techniques. Common methods include extreme learning machines, artificial neural networks, support vector machines, decision tree algorithms, and so on. With the invention and application of various optimization algorithms, detection technology has become closer to actual detection situations, resulting in more accurate detection results after processing [6].

5. The limitations of the development of electromagnetic detection methods

In recent years, various universities and related enterprises at home and abroad have invested a lot of manpower and material resources in the research of electromagnetic testing methods for steel wire ropes, and have achieved considerable results. However, the quantitative testing results have not yet met the expected requirements, and a relatively complete and systematic effective method has not been formed.

(1) Excitation structure design: The excitation structure is the foundation of uniformly magnetized steel wire rope, and the strength of the magnetic field will have varying degrees of impact on the detection results. The designer determines the structural design parameters of the exciter based on finite element simulation or previous experience, and has not conducted extensive practical testing, so there is no theoretical basis for the design method of the exciter.

(2) Sensor design: The core of designing sensors lies in the selection of sensors and array design. Although there are currently multiple types of sensors available, they also have specific application requirements that cannot simultaneously meet the needs of high sensitivity, high resolution, good temperature stability, simple installation and design, and cannot be promoted and used.

(3) Feature extraction and quantitative recognition: Extracting the damage signal characteristics of steel wire ropes is a necessary condition for non-destructive testing and quantitative identification. There is a certain correspondence between certain damage characteristics of steel wire ropes and the characteristics of detection signals, but it still cannot meet the conditions for quantitative identification. Feature extraction mainly faces three challenges: lack of reasonable and effective feature extraction methods, lack of interpretable feature extraction results, and lack of systematic data collection and processing methods. At present, there are shortcomings in quantitative identification, such as inadequate accuracy of local damage quantification, difficulty in quantifying internal damage and corrosion damage, which cannot meet the established requirements for detection.

(4) Reliability of test results: For the entire steel wire rope, minor damage, low magnetic flux leakage intensity, and complex testing processes can all have varying degrees of impact on the testing results. In addition, the detection signal of steel wire rope is easily affected by external environmental factors, such as electromagnetic interference and temperature and humidity changes, which can have adverse effects on it, reduce the signal-to-noise ratio of the output signal, increase the difficulty of detection, and make it difficult to ensure the reliability of the detection results.

6. Prospects for non-destructive testing of steel wire rope

With the arrival of the aging population era, the young labor force has also decreased, forcing the detection of steel wire ropes to rely on intelligent detection. Non-destructive testing of steel wire ropes also urgently needs rapid development and breakthroughs, which can be approached from the following aspects:

(1) The simulation model of the steel wire rope aims to replicate the multi wire twisting structure of the steel wire rope as much as possible, create a simulation model that is close to reality, simulate steel wire rope samples of various types of damage, and seek effective methods for quantitative detection of steel wire rope LMA based on the feedback of magnetic signal characteristics for LMA type damage [7].

(2) Realize multi-sensor fusion detection [8]: A single sensor is difficult to obtain all the information about wire rope damage and cannot meet the qualitative analysis of multiple types of damage. Therefore, multiple sensors are often fused to detect damage. However, the detection principles and methods of different sensors vary, and as the amount of data increases, the difficulty of signal processing also increases. To ensure the reliability of multi-sensor fusion detection, higher requirements have been put forward for computing power.

(3) Research on high-speed magnetic leakage: Currently, magnetic leakage research and detection equipment are generally based on low-speed operation of steel wire ropes. However, for actual working conditions, especially for online monitoring, the demand for high-speed operation is becoming increasingly strong. During the high-speed operation of steel wire ropes, there may be problems such as detection speed not keeping up with the running speed, and many complex electromagnetic phenomena and signal distortions caused by dynamic magnetization have emerged, and effective methods have not

yet been found to solve them. Therefore, further research is needed on the single detection method and multi-method coupling that can adapt to high-speed magnetic flux leakage detection [6].

(4) Quantitative detection of LMA damage amount: LMA damage quantitative detection is an important parameter for non-destructive testing of steel wire ropes, which can serve as an important basis for comprehensive evaluation of the remaining strength of steel wire ropes and provide quantifiable damage indicators for life evaluation, thereby providing a more accurate basis. The maintenance and replacement cycles of subsequent steel wires can be determined based on the quantitative results of LMA damage, in order to avoid steel wire rope breakage accidents, which may cause casualties and unnecessary economic losses [7].

(5) Accumulation of sample library: The determination of wire rope damage is based on the analysis process of actual wire rope damage samples. The accuracy of existing methods cannot meet practical needs. The latest method is to use convolutional neural networks to evaluate the defect size of magnetic flux leakage detection signals, improving the detection recognition rate [8]. The neural network algorithm is based on a large database of training samples to ensure high-precision calculation of multi-parameter quantification of defects. However, the actual production of a sufficient number of standard defects in steel wire ropes requires huge manpower and material resources, and on-site sampling of working conditions is even more difficult and dangerous. Different steel wire ropes and detection equipment also need to be retrained, making it difficult to promote and use this method. So, the accumulation of sample libraries is very necessary.

In the future, if we want to widely apply non-destructive testing of steel wire ropes, it will inevitably require a long-term accumulation process, and even the technical support of the entire industry to achieve the accurate results we expect.

Disclosure statement

The authors declare no conflict of interest.

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