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Review

A Comprehensive Review of Steel Wire Rope Degradation Mechanisms and Recent Damage Detection Methods

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Abstract: Steel wire ropes are the vital load-bearing element in many rope transport devices, such as mine hoists, personal lifts, bridges and cableways. Non-destructive fault detection is a crucial issue for safety and reliability. This paper presents a comprehensive review covering three areas: damage mechanisms for steel wire ropes, physical phenomena used for diagnostics of steel wire ropes and practical applications of magnetometers. The advantages and disadvantages of each group of sensors, such as the induction coil, Hall element, magnetoresistance and optically pumped magnetometers, are presented. The author indicates the direction of the development of signal analysis techniques. In summary, the challenges and future directions for the development of wire rope flaw detection in practical applications are presented, especially considering the future of passive magnetic methods.

Keywords: steel wire ropes; non-destructive testing; review; passive magnetic methods

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Citation: Mazurek, P. A Comprehensive Review of Steel Wire Rope Degradation Mechanisms and Recent Damage Detection Methods. *Sustainability* **2023**, *15*, 5441. https://doi.org/10.3390/su15065441

Academic Editors: Francesco Tajani and Shuhua Fang

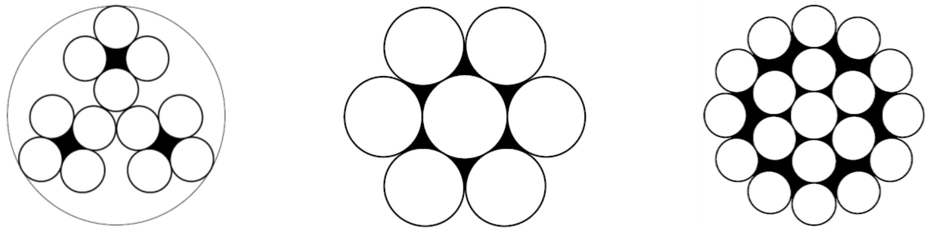
Received: 7 February 2023
Revised: 5 March 2023
Accepted: 17 March 2023
Published: 20 March 2023

1. Introduction

The United Nations Brundtland Commission defined sustainability in 1987 as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". The easiest way to maintain sustainable development is to save available resources. A method that may be conducive to this is non-destructive testing of elements for which suitability is not certain. This article focuses on the non-destructive testing of wire ropes. Replacing them prematurely can lead to overuse and overproduction. With each such exchange, there is also an energy demand. There is, moreover, no doubt that more frequent replacement of steel wire ropes can cause problems with their disposal, especially for ropes in the form of belts or steel ropes with a polyurethane cover.

Steel wire rope is one of the most commonly used load-bearing elements in industry. The very high strength of the wires allows the ropes to transfer high tensile and bending forces by bending through pulleys with relatively small diameters. This very high strength, which impacts the spread of ropes, has been known for over a hundred years since an exceptional heating and drawing process was patented. Many books describe, with a broader or narrower scope, aspects related to the production and use of steel ropes. Their production began on a large scale in 1834 thanks to Oberbergrat Wilhelm August Julius Albert. One of the first relevant books was Benoit's published in 1935; the studies by Verreet (1988), Sayeng (1997, 2003), Feyer (2017) [1] and Tytko (2021) [2] deserve attention. Each of these items is extensive, and the approach to ropes is treated holistically. In this work, I present only selected essential facts from a practical point of view.

The world's first steel rope, the so-called "Albert's rope", was 18 mm in diameter; it consisted of three strands of four wires, each with a diameter of approx. 3.5 mm. Interestingly, it was twisted by hand. On 23 July 1834, in the Karolina mine near Clausthal, at a depth of 484 m, it successfully performed its function. Undoubtedly, the most significant advantage of this rope was that each of its wires was visible from the outside, allowing it to be effectively diagnosed and replaced at the right time. The development of industry forced the creation of new rope structures with larger diameters and more significant numbers of wires. The concept of placing a wire/strand in the centre and the other wires/strands around it was born. Basic structures of steel wire ropes and strands are shown in Figure 1. From the perspective of diagnostics, this was unfavourable—it was no longer possible to inspect all wires, especially the central one (core), which was utterly invisible [3]. Undoubtedly, this provided the impulse for the development of other methods of wire rope diagnostics.



(**a**) (**b**) (**c**)

Figure 1. Basic structures of steel wire ropes/strands: (**a**) structure of Albert's rope; (**b**) strand 1 + 6; (**c**) strand 1 + 6 + 12.

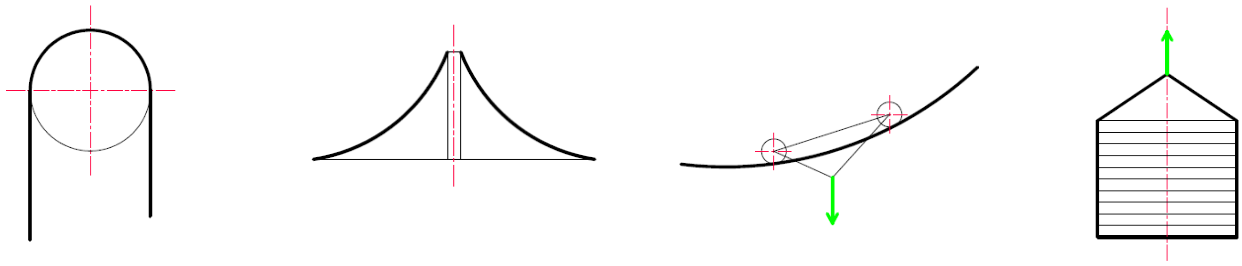
The most systematized study on the diagnosis of steel wire ropes is [4]. This work describes in detail the known methods of wire rope diagnostics and presents the sensors' characteristics, thoroughly analysing their disadvantages, advantages and potential for use. It is crucial to describe signal analysis techniques. Unfortunately, this work does not contain basic information about steel ropes—the damage mechanisms and the different types of work in other environments. This information appears in [5]. The authors of the work quite thoroughly show the types of damage steel ropes can sustain, for which they indicate the appropriate diagnostic method. However, this work is not very up-to-date; the development of steel rope diagnostics is very dynamic. Much new research has been undertaken to support the development of diagnostics. Ref. [6] deserves special attention. This work only focuses on magnetic sensors, but the review is comprehensive and meticulous. It includes sensors using the following phenomena: the Hall effect, tunnel magnetoresistance, anisotropic magnetoresistance and giant magnetoimpedance. Complementary in the context of steel rope diagnostics is [6]. In this work, the researchers present, in addition to a detailed description of the mechanisms of steel rope wear and their causes, supported by physical explanations, a rich review of the literature in which the given issue is discussed.

The aim of this work was to provide an even more thorough systematization and update of the information included in the previously mentioned publications. An essential aspect of this publication is the combination of information on both wire ropes and their diagnostic methods. However, the work focuses on the most dynamically developing branch of diagnostic methods using passive magnetic techniques. The author's contribution to the development of this field of diagnostics is presented. The directions of development of the methods described in detail are also indicated, including their opportunities and threats for application in industry. An inseparable element of the work is the aspect concerning sustainable development of the environment, which, through skilful diagnostics of steel ropes, will allow for less frequent replacement of load-carrying strands. Currently, installed rope-transport devices—especially steel wire ropes, ropes with polyurethane coatings, and belts with plastic coatings [7]—are becoming increasingly popular. Their premature replacement and associated disposal is a problem that can be solved thanks to the research described here.

2. Damage Mechanisms for Steel Wire Ropes

2.1. Basic Information about Steel Wire Ropes

Depending on the use of wire ropes, they must meet certain requirements. These requirements impose a specific structure, diameter and strength to be selected when designing a given system [1]. The primary division of steel ropes by application is shown in Figure 2.

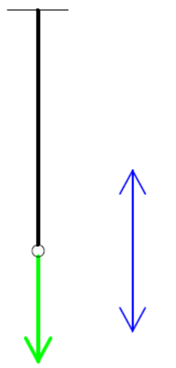
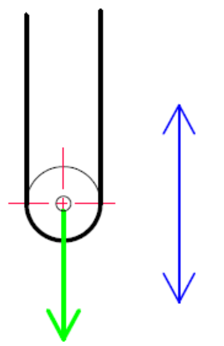
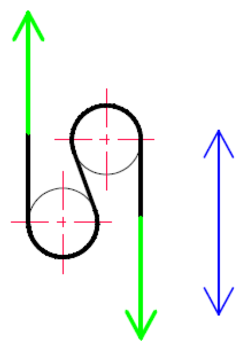
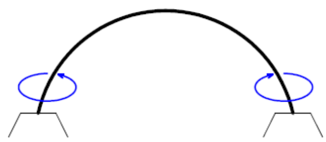
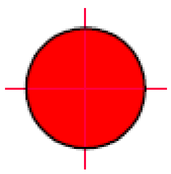
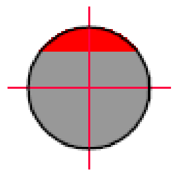
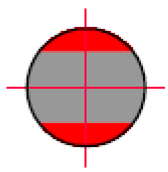
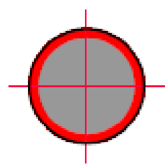


(**a**) (**b**) (**c**) (**d**)

Figure 2. Types of ropes according to their use: (**a**) running rope; (**b**) stationary rope; (**c**) track rope; (**d**) rope sling.

The wire systems used in fatigue tests, zones of maximum stress amplitudes in the wire cross-section, stress amplitudes and average amplitudes are presented in Table 1. Knowing this information allows us to predict the life of a rope and plan diagnostic tests [1].

Table 1. Wire systems used in fatigue tests, zones of maximum stress amplitudes in the wire cross-section, stress amplitudes and average amplitudes.

	Tension	Simple Bending	Reverse Bending	Rotary Bending
Wire arrangements for testing				
Zone of maximum fluctuating stress				
		Stresses		
Stress amplitude Middle stress	$\sigma_a = \sigma_{t,a}$ $\sigma_m = \sigma_{t,m}$	$\sigma_a = \frac{\sigma_b}{2}$ $\sigma_m = \sigma_{t,m} + \frac{\sigma_b}{2}$	$\sigma_a = \sigma_b$ $\sigma_m = \sigma_{t,m}$	$\sigma_a = \sigma_b$ $\sigma_m \approx 0$

2.2. Damage Mechanisms for Steel Wire Ropes

Steel wire ropes are subject to damage during regular operation, which reduces their strength and threatens systems' safety. The most common reason for replacing wire ropes is damage to only a specific section where the number of wire breaks exceeds the acceptable level. This negatively impacts sustainable development—in many cases, these ropes are automatically scrapped, but large sections (separate from the damaged ones) could still be successfully used for operations. This highlights the importance of the development of wire rope diagnostics [8].

Damage to steel ropes can be divided into two groups: local damage (local faults/local flaws (LFs)) and loss of cross-section (loss of metallic area (LMA)) [9]. LFs are defined as short discontinuities in wire ropes, such as wire breakage, welded wire, corrosion pitting or nicks between the strands. LMA is a change in the metallic cross-sectional area expressed as a percentage of the nominal metallic cross-sectional area relative to the new rope [10]. This type of damage to steel ropes is described in [11].

Types of wire damage (local damage) are shown in Figure 3.

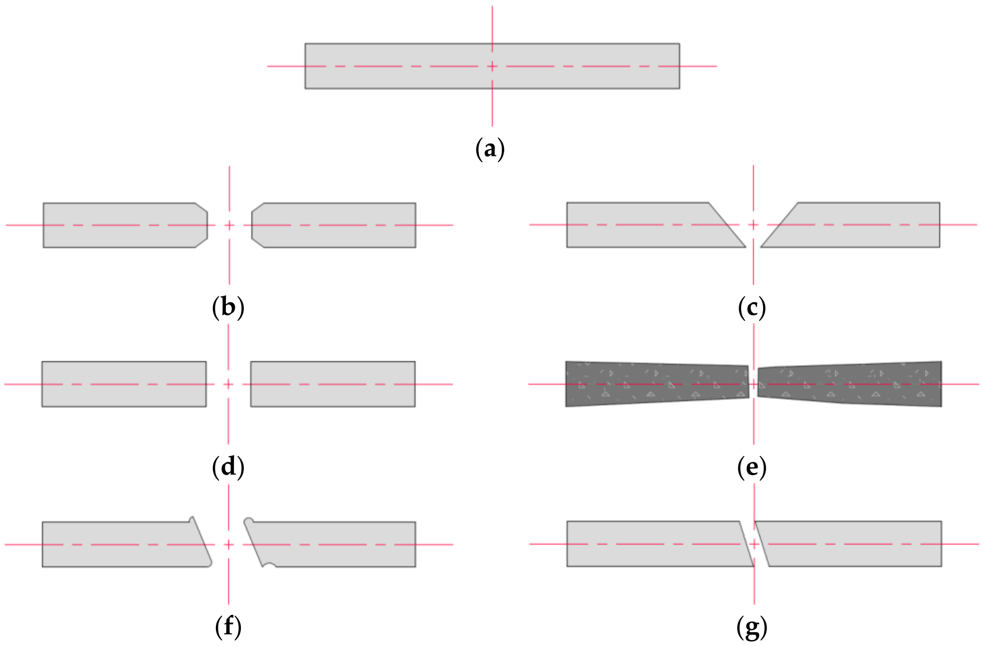


Figure 3. Types of LF loss: (**a**) no loss; (**b**) overload; (**c**) wear; (**d**) fatigue; (**e**) rust; (**f**) kink; (**g**) cut.

Wire ropes are used in almost every industry and have many different applications. As a result of continuous use, they inevitably degrade. This degradation is often caused by four phenomena: fatigue, frictional fatigue, wear and corrosion. These phenomena may occur alone, but they almost always occur in various combinations and with varying intensity [12].

Sudden breakage of a rope can endanger people's lives and health and cause costly downtime. Therefore, accidents resulting from damage to steel ropes are a severe problem and a challenge for designers and constructors, especially regarding the safety of human life. The basis for improving the efficiency of rope use is increasing safety and a good knowledge of the degradation process. The fatigue processes above have the most significant impact on the development of degradation [6]. The most common degradation mechanisms are presented in Table 2.

Table 2. Main degradation mechanisms for steel wire rope.

Degradation Mechanisms	Main Causes	Dominant Parameter	Application Areas
Tension–tension fatigue	Changes in the axial tensile loading	Tensile load range	Lifting and hoisting applications, including mine hoisting
Bending-over-sheaves fatigue	Local changes in wire curvature as the rope adapts to the radius of a sheave or drum	The D/d ratio (the ratio of the sheave diameter to the rope diameter) Tensile load	Lifting and hoisting applications Mooring ropes
Free-bending fatigue	System dynamics or lateral oscillation	Tensile load	The cables of cable-stayed suspension bridges
Torsion fatigue	Absence of restriction on rotation under the attachments at either end No compliance with the restraint	Twist amplitude	Mooring of floating offshore systems Lifting and hoisting applications
Fretting fatigue	Friction between contacting wires	Coefficient of friction	All rope applications
Corrosion	Temperature, pollutants in the air and water	Water temperature	Mooring ropes The cables of cable-stayed suspension bridges
Wear	Friction between wires Bending of the rope	Coefficient of friction Bending stresses over sheaves or drums	Lifting and hoisting applications Mooring ropes

2.3. Previous Research on the Propagation of Damage in Steel Ropes

The wearing of steel ropes results in the deterioration of their operational parameters, which may threaten the safety of people using rope-transport devices. The authors of [13] proved that surface wear contributes to crack propagation. This is a scary situation, which, in the worst case, may result in the strand or the entire rope breaking. Broken wires in wire rope affect the tension state of the entire rope, concentrating the propagation of cracks. This leads to faster wear and the need to replace the rope. The currently used criterion for the rejection of steel ropes consisting of counting broken wires is inadequate for actual conditions, resulting in premature replacement of ropes [14]. Undoubtedly, such a solution disrupts the sustainable development of the environment because these are not exceptional situations but the currently used standard. The still unresolved problem of effective diagnostics for steel ropes in mine hoists forces the search for new solutions. One such solution is the proposal described in [15]. The authors present a model that uses the principle of balancing the magnetic field to design a structural model of magnetic focusing. This solution seems to be particularly useful for ropes with large diameters. Unfortunately, this is an active method that requires an external source of magnetization, which is contrary to the sustainable development of industry. In subsequent work, the authors attempted to diagnose steel ropes using real objects in real time. For diagnostic and operational reasons, it is not only the discontinuities in the rope (damage) that are important but also the stresses occurring. The authors of [16] describe the use of a sensor with a vibration dissipation function. This is very important for the diagnostics of working objects: vibrations effectively hinder correct diagnostics. Unfortunately, the obtained results are not satisfactory. The authors of [17] analyse the external magnetic field's influence on ferromagnetic material's stress intensity factor. It has been proved that magnetic field disturbances are greatest in the initial stage of mechanical loading. Ferromagnetic structures are already magnetized at the manufacturing stage. The change in magnetization (Hp) in the initial phase is linear. Plastic deformation reduces magnetic permeability, and self-magnetization of local stress concentration zones develops, causing nonlinear changes [18]. In [19], theoretical and experimental studies were conducted to determine fatigue life as a criterion for laying down a non-swivel rope with alternate bending. As a result of the experimental research, it was proved that the life of the Na rope decreased with the load and the decrease in the diameter of the pulley through which it was bent. A very high correlation between the experimental results, the artificial neural network (ANN) and the results of the proposed regression model was shown. Nevertheless, an unsolved problem in the diagnosis of steel ropes is the diagnosis of the inner strands of steel ropes and the core. In [20], the authors conducted experimental tensile tests on steel ropes with modelled damage. Ye Duyi damage models and the Weibull distribution were adopted. Both models describe the behaviour of the core well and make it possible to predict the critical areas of ropes. The fault detection algorithm proposed here was based only on statistical analysis and works well in general. Ropes have complex states of stress and different degrees of damage to individual strands, disqualifying this method for use as part of diagnostics in industry. Publication [21] analysed in detail fatigue tests for steel ropes. The sequence of damage growth was presented. Cracks are a complex effect of fatigue, bending and contact stresses. A model of the steel rope was even developed and subjected to numerical analyses, which were confirmed by the conducted research. In [22], attention was paid to the corrosion of steel rope wires and its impact on the rope's life. Tests showed that the maximum strength and crack resistance decreased with increasing immersion time in a 30% sulphuric acid solution. Among the various models, Erismann's law was chosen as the one that could best describe the life curve of a steel rope in corrosive conditions. Similar research was described in [23], except that the focus was on a single wire in this case. Fatigue tests were carried out on wires with various degrees of corrosion. A model describing the durability of the steel wire, taking into account the influence of corrosion, was also proposed. The analysis described in [24] aimed to comprehensively examine the degree of fatigue damage to steel ropes, considering torsional stresses. For this purpose, a fatigue machine was built and measurements were carried out. Wire breakage develops slowly at the beginning of the fatigue stage but rapidly when fatigue times exceed 60,000 cycles. In [25], it was shown that the transverse angle between wires significantly impacts the wear marks and the mechanical properties of the wires. The test results in [26] showed three types of component stresses in the rope cross-section: tensile, shear and bending. In most previous studies, only tensile stress was considered when investigating strength and fatigue. However, bending and shear stresses were also found to be important factors here.

3. Non-Destructive Detection Methods for Wire Ropes

The primary non-destructive testing methods currently known and used for wire-rope testing are magnetic flux leakage (MFL), eddy current testing (ECT), acoustic emission (AE), ultrasonic guided waves (UGWs), radiography and vision testing. Each method uses different physical phenomena, and there is intensive research being conducted on almost every method.

3.1. Magnetic Flux Leakage (MFL) Method

Magnetic flux leakage is one of the most commonly used methods for wire rope diagnostics [27]. This method is also used in many other industries where the reliability of ferromagnetic components is essential, such as for the diagnosis of steel pipes [28,29] or bridge support components [30]. A rope with LF- or LMA-type defects is subjected to magnetization by a strong external magnetic field. It is possible to pinpoint defect locations by changing the magnetic resistance with suitable sensors, such as an induction coil or Hall effect sensor [31]. The operating principle is illustrated in Figure 4.

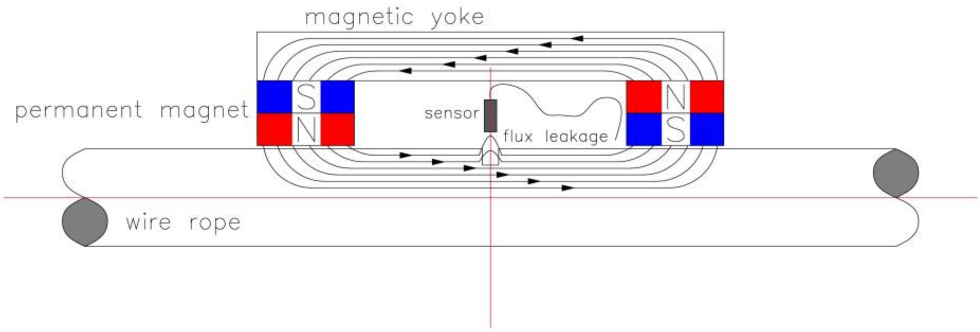


Figure 4. Principles of typical MFL testing method for wire rope.

The magnetic flux leakage used for wire rope diagnostics is described in [32]. The authors demonstrated high sensitivity and repeatability for their measurements, but the method used permanent magnets for additional magnetization. This affected the size of the measuring system. In [33], a numerical simulation was carried out to identify the value of and variation in magnetic flux density with regard to defect depth. Unfortunately, the tests were carried out for a steel bar, which is a homogeneous material. Therefore, the results for steel wire rope may differ from those obtained. The authors of [34] proposed a novel magnetic shielding (MS) technology that should improve the quality of the magnetic flux leakage (MFL) signal. Unfortunately, inconsistencies between the experimental results and the simulation significantly limit the application of this technology. Researchers are looking for reasons for these discrepancies. The shielding effect is most effective for long faults with shallow depth. The high speed of wire ropes results in vibrations, making it challenging to carry out meaningful measurements. Worse still, it can result in skewed results and wrong decisions regarding rope operations. The authors of [35] proposed a radial magnetic concentrator supported by theoretical analyses. Undoubtedly, this is a crucial step in diagnostics, but the fact remains that a large-scale apparatus must be used for the test, requiring the magnetization of the test object with a strong magnetic field. This contradicts the aims of sustainability. The authors of [36] used magnetic flux leakage (MFL), introducing the slotted ferromagnetic lift-off layer. Compared to the conventional method with an air gap present, the ferromagnetic gap has been proven to be more effective. The gap occurring in the ferromagnetic layer enhances the diagnostic signal. However, a problem arises when diagnosing complex components and components with defects, as the introduced ferromagnetic layer could be damaged during the measurement. In [37], an alternating current magnetic flux measurement (AC-MFM) method was compared with the permanent magnet magnetic flux measurement (PM-MFM) method. The superiority of the PM-MFM method over the AC-MFM method was demonstrated, mainly due to the speed of the measurements. The experimental analysis confirmed that the proposed PM-MFM sensor was compatible with various ferromagnetic materials, allowing broad industrial applications.

3.2. Eddy Current Testing (ECT) Method

Eddy current testing (ECT) is a commonly used non-destructive testing technique for detecting defects in metal structures. In [38], the researchers developed miniaturized single-channel and dual-channel probes based on tunnel magnetoresistance. The application of this method to wire rope diagnostics is described in detail in [39]. The principle of operation is described in detail in [40] and schematically illustrated in Figure 5.

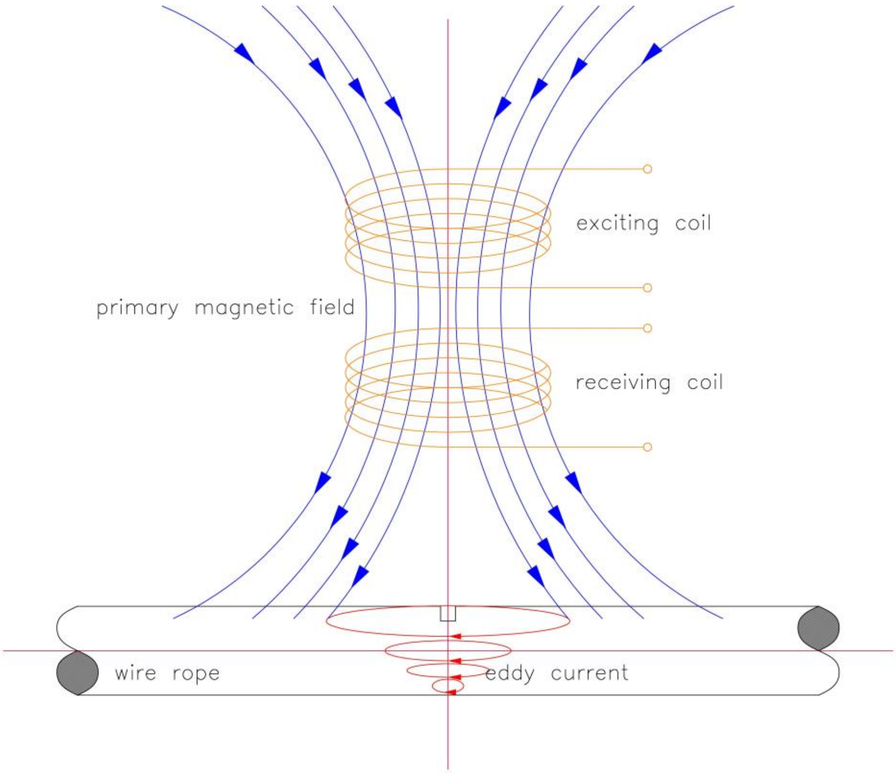


Figure 5. Principles of typical ECT method for wire rope.

The authors of [41] used different eddy current-based probe designs for defect detection: total and commercial reflection. The experimental results showed that the absolute probe was suitable for detecting cracks and holes, while the reflection probe was more suitable for detecting subsurface defects, such as small-diameter blind holes. This is a fundamental observation in the context of detecting defects both on the surface and in the interior of the test object. Article [42] addresses the problem of detecting defects with different orientations relative to the direction of the eddy currents. The authors designed a special probe based on a triaxial magnetic sensor. Simulation results confirmed the superior performance relative to the uniaxial sensors most commonly used in industry. The effectiveness of the triaxial magnetometer was also proven in [43]. The application of ECT for further research on wire ropes requires solving the problems related to skin effects and eddy current losses.

3.3. Acoustic Emission (AE) Method

The acoustic emission method has been successfully used to diagnose high-pressure pipes [44]. Due to the physical mechanisms causing defects in steel cables (cracks, stress concentrations, corrosion), even small changes can be detected by a sensor built with piezoelectric transducers. Many authors are working on the development of this method [45]. The principle of operation is described in [46] and schematically shown in Figure 6.

The development of this method for wire rope diagnostics has been noticeable in recent years. Most authors focus on signal analysis [47,48]. Of particular interest in relation to acoustic emission methods is the phenomenon of Barkhausen noise. The authors of [49,50] investigated the correlation between corrosion defects and Barkhausen noise. Unfortunately, this method does not work well for different wire thicknesses and diameters and in situations involving accumulated defects, especially under harsh operating conditions (corrosion, grease, etc.).

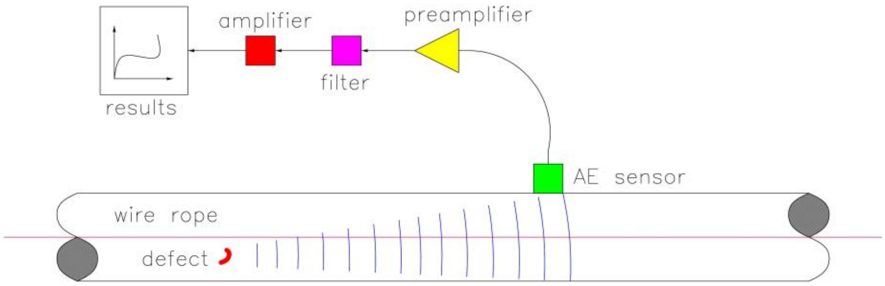


Figure 6. Principles of typical AE testing method for wire rope.

3.4. Ultrasonic Guided Wave (UGW) Method

In contrast to acoustic emission, the ultrasonic guided wave method is a non-destructive active method. Its operating principle is shown in Figure 7 [51]. The most important part of the system is the piezoelectric transducer, which is used to generate and detect the guided wave [52].

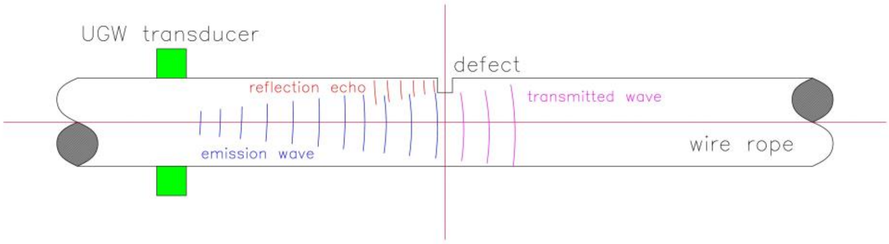


Figure 7. Principles of typical UGW testing method for wire rope.

An ultrasonic testing technique to identify individual damaged wires inside the internal structure of strands was developed [53] and verified experimentally. Longitudinal guided waves for wire rope diagnostics were described in [54]. The authors noted a difference in the results obtained depending on the rope's tension. A detailed analysis would require further research focusing on the appropriate polarisation of the magnetic field. Article [55] presents a detailed analysis of magnetic field reconstruction using pulse-wire methods. This is an innovative method, the results of which depend on the pulse length. The results obtained in this study could be more reliable, despite the numerical simulations performed. The method needs to be refined. The authors of [56] pointed out the disadvantages of the proposed innovative pulse-wire magnetic method. Due to the frame's unique design, it is impractical for measurements of real objects and costly. The method is also fraught with internal sources of error that disturb the results' reliability level. Despite the signal analysis algorithm proposed by the authors, this method still requires very detailed analysis for practical use.

3.5. Radiography

Radiographic testing is a standard non-destructive testing method that has also found applications in the diagnosis of steel wire ropes. The steel wire rope absorbs part of the radioactivity; the rest of it penetrates through the tested rope and is projected onto a film, where a defect image is produced. The degree of absorption and penetration of steel rope radiation depends on many factors relating to the material being tested, such as the density, diameter, construction, and air gaps. Depending on the radiation source, the method can be divided into two groups: X-rays [57] and gamma rays. The detailed principle of the method is illustrated in Figure 8.

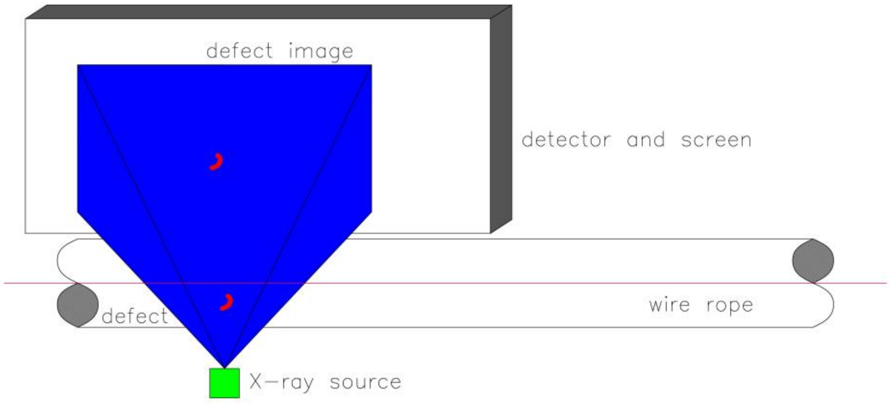


Figure 8. Principles of typical radiography testing (X-ray source) method for wire rope.

This method's basics are thoroughly described in [58]. The authors pointed out how important it is to select the proper test objects. Gamma radiation has been successfully used to diagnose steel bridge cables [59]. The use of this method in wire rope diagnostics is manifesting as a development trend. However, as radiation can cause harmful effects on human health and the test equipment is of considerable size, there are many challenges and problems to be addressed [60].

3.6. Visual Inspection/Thermal Imaging

Visual testing is undoubtedly one of the non-destructive methods of wire rope diagnostics [61]. Unfortunately, visual inspection is often insufficient to visualize all defects [62]. Machine vision support (the machine vision method) [63,64] or thermal imaging studies are often required [65]. Termovision tests are also used to determine the service life of wire rope [66] and evaluate geometric parameters [67]. The principle of operation is described in [68] and schematically shown in Figure 9.

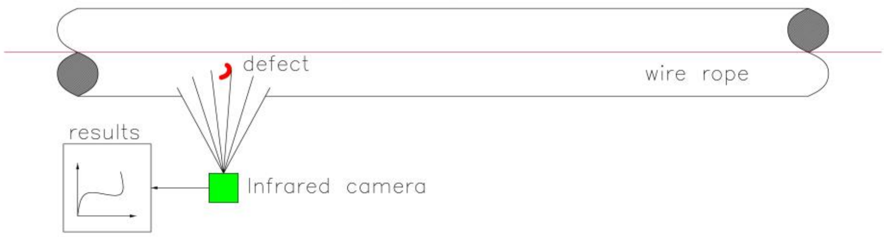


Figure 9. Principles of typical induction thermography method for wire rope.

The experiments conducted in [69] showed that, as the load on the steel cables increases, the temperature also rises through the increase in stress. These tests require other measurements, as thermal imaging alone is insufficient to unambiguously determine the critical cross-section of the test object. Thermal imaging, due to its elementary operating principle and, especially, its independence from the rope materials' mechanical, electrical and magnetic properties, is suitable for rapidly detecting highly loaded load-bearing ropes with different cross-sections. The studies in [70] showed that the thermo-elastic effect occurs in compacted ropes during uniaxial loading. Measurements of the average surface temperature of the specimens between loading cycles showed that the processes occurring in the internal structure of the rope during elongation (mainly friction) caused temperature changes. Magnetic thermography testing (MTM) signals caused by the leakage of residual magnetic flux from corrosion defects in the tube were confirmed with experimental testing. As the distance and propagation of the defect signal increase, the amplitude decreases and the risk of interference from nearby ferromagnetic objects increases. Weak defect signals at large distances and the possibility of interference from relatively distant ferromagnetic objects, such as bolts, nuts, etc., are likely reasons for the high false-connection rate observed in some trials of this technique [71]. One of the most recent methods of wire rope diagnostics is infrared thermography. An experiment in [72] showed how many factors affect the measurement result. In addition to the structural parameters of the rope, these factors include the ambient temperature, the temperature of the sample and the reflection temperature. This is not a significant problem under laboratory conditions, but performing this type of test under natural conditions may result in a significant measurement error. Another problem is the proper calibration of the camera, which also affects the measurement result. In [73], a novel approach was proposed to diagnose wire ropes based on texture features. Attention was paid to the choice of illumination and appropriate filtering algorithms. Unfortunately, these algorithms only focus on defects occurring in the outer strands of the ropes and do not consider defects occurring in the wires inside the ropes.

3.7. Comparison of Wire Rope Diagnostic Methods

Using the appropriate method for a specific application requires the diagnostician to have extensive knowledge and experience. It also requires basic physical knowledge regarding each of the mentioned methods. Including all of this here would make comprehension much more difficult. Therefore, in Table 3, only the shortcomings, advantages and applications of particular methods and the possibilities for quantitative and qualitative assessment are presented. However, this does not indicate the limits of these methods' diagnostic capabilities; depending on the knowledge and experience of the diagnostician, it is possible to detect defects not described in this table.

Table 3. Main methods of wire rope diagnostics.

Method	Advantages	Disadvantages	Application Areas	Assessment
MFL	– Inexpensive – Straight – Reliable – Suitable for initial quantitative measurements – Possibility of online testing	– Defects inside the rope are difficult to distinguish – The distance from the sensor plays an important role – Time-consuming study	– Broken wires/strands – Wear – Clash – Corrosion	Quantitative assessment (the value of the difference in magnetic induction corresponds to the size of the damage)
ECT	– Sensitive to metal materials – Suitable for high speeds – Suitable for high temperatures	– Skin effect – Limited to the detection of defects on the surface only – Low effectiveness of inspections	– Surface defects – Pitting	Qualitative assessment
AE	– Suitable for composite materials – Detection of defects at an early stage	– Is only applicable to dynamic processes – Very low signal-to-noise ratio	– Broken wires/strands – Stress concentration – Corrosion	Qualitative assessment
UGV	– Detects defects inside the rope	– Only for qualitative assessment – Details of a defect are complex to explain	– Broken wires/strands – Corrosion	Qualitative assessment

Table 3. *Cont.*

Method	Advantages	Disadvantages	Application Areas	Assessment
Radiography	– Intuitive test results – Reliable	– Costs (expensive research equipment) – Harmful to health – Environmental pollution	– Broken wires/strands	Qualitative assessment
VT	– Ease of implementation – Low cost – High detection rate	– Control of near-surface defects – Need for good lighting – The test surface must be cleaned	– Broken wires/strands – Corrosion	Qualitative assessment

4. Recent Passive Magnetic Techniques and Sensors

According to the characterization presented in the previous section, there is no doubt that magnetic methods are the most popular among non-destructive methods for wire rope diagnostics. It is complicated to provide a systematic classification of magnetic sensors. According to [74], the most popular magnetic NDT methods can be divided into magnetic flux leakage (MFL), magnetic Barkhausen noise (MBN) and metal magnetic memory (MMM). This is a division from 10 years ago when the diagnostic capabilities of metal magnetic memory were beginning to be discovered. From the perspective of wire rope diagnostics, it seems much more reasonable to divide them into two groups: active techniques requiring the magnetization of the test object with a strong external magnetic field and passive techniques using the test object's magnetic scattering field.

4.1. Active Magnetic Techniques and Sensors Used

One of the first studies detailing the active magnetic methods in wire rope diagnostics was [75]. In many countries, state criteria for the diagnosis of rope-handling equipment are based on tests using this technique [76]. An overview of the sensors used in China can be found in [77]. According to [78], selecting a suitable sensor depends on the fault that is sought: for LF-type faults, inductive sensors should be used, while for LMA-type faults, Hall sensors should be used.

4.1.1. Inductive Sensors

Inductive sensors use Faraday's law of electromagnetic induction. In diagnostic practice, many different types of induction coil are used: planar coils, Rogowski coils, triaxial coils and flexible printed coils [79]. A detailed overview of the different types with descriptions is presented in [80]. New sensor designs based on electromagnetic induction have not been reported recently. The biggest problem is the low sensitivity and accuracy of microcrack detection, which all researchers strive to improve [81]. Furthermore, a new trend for the future of non-destructive testing is represented by radio-frequency ID (RFID) inductively powered devices and sensors. All use the induction coil method as part of the core and improve the range of applications and the detection sensitivity [82]. Induction coils are also sensitive to single-wire features and noise signals, which increases the difficulty of distinguishing wire rope damage signals. In addition, induction coils are also sensitive to changes in the speed of the detectors from which they are formed, making the output signal more complex to analyse. As a result, they are challenging to use for online wire rope monitoring and inspection due to the varying operating speeds.

4.1.2. Hall Effect Sensors

Another important magnetic sensor in wire rope diagnostics is the Hall effect sensor, which is mainly based on the Hall effect. According to the principle of the Hall effect, the Hall sensor and the control signals are independent of the scanning speed. This is particularly useful for online wire rope testing and identifying defect sizes in quantitative non-destructive testing. Furthermore, the output signals of the Hall element are directly related to the absolute magnetic field strength, which makes the Hall sensor particularly suitable for metal cross-sectional area (LMA) loss detection of defects such as abrasion and corrosion. Research on the Hall element has mainly focused on improving the sensor's sensitivity, and the measurement dimensions have been increased from one to three. Hall sensor arrays have also been widely used for complex sensing conditions, such as high temperatures and speed. In [83], a magnetic concentration sensor was comprehensively investigated for the detection of wire rope damage. The sensor used a concentrator to help the Hall component collect the MFL caused by the defects. Simulation results showed that the magnetic concentration sensor could collect the MFL produced by the defects more effectively. The newly designed excitation system proposed in [84] has a much lower weight and size than the classical sensor. The newly designed system suppresses the signal noise well, thus improving the defect signal to magnetic image noise ratio. All simulated defects were identified, and defects in the same axial position could be distinguished. Despite the size reduction, the technique still requires magnetization with an external magnetic field, and the device's size makes it challenging to carry out measurements of real objects.

4.2. Passive Magnetic Techniques and Sensors Used

The metal magnetic memory (MMM) technique was first developed by Dubov [85]. This method is based on the principle of self-magnetic flux leakage (SMFL), which is similar to that of MFL, but it does not involve actively magnetizing the sample [86]. It uses the Earth's magnetic field as the only external source. In addition to the Earth's magnetic field, there are also internal sources of magnetization, such as permanent magnetization due to remanence and stress magnetization [87,88]. The metal magnetic remanence technique, compared to the traditional magnetic method based on magnetic field flux leakage, has a lower cost and easier handling. The number of studies on self-magnetic flux leakage needs to be increased, and controversy around this method still exists. In [89], the relationship between the magnetic signal and the existing stress state was presented. In recent years, interest in this method has increased, as evidenced by the rapidly increasing number of publications on the subject [90–93]. The physical basis of this method has been successfully used to measure stresses [94,95], as well as for the measurement of discontinuities [96]. In the field of wire rope diagnostics, these sensors are used to determine the condition of ropes [97,98]. They have been successfully used both to assess the strain in wire ropes due to bending and to detect broken wires. They allow qualitative and quantitative assessments [99,100]. The main types of sensors in the field of passive magnetic diagnostics are magnetoresistive and optically pumped sensors.

4.2.1. Magnetoresistive Sensors

A magnetoresistive (MR) sensor consists of two thin layers of magnetic material separated by a layer of non-magnetic metallic material. Naturally, the MR sensor can be used for effective detection of wire rope defects due to its mechanism of changing resistance and thus producing current when the magnetic field detected by the sensor changes. With the identification of the MR effect, various MR sensors have been proposed, such as the giant magnetoresistance (GMR) sensor, tunnel magnetoresistance (TMR) sensor and anisotropic magnetoresistance (AMR) sensor, based on the physical phenomena of giant magnetoresistance, tunnel magnetoresistance and anisotropic magnetoresistance, respectively, and they have significantly improved the sensitivity of magnetic field detection. The structures of three typical MR sensors are shown schematically in Figure 10. Some researchers are still engaged in optimization of MR sensors and new MR sensor designs, aiming to improve the inspection system's stability further and develop MR theory. With regard to the sensors reported in the literature, the sensitivity is highest for GMI sensors but, due to their size and high cost, they have yet to find applications in wire rope diagnostics [101]. They are followed by TMR, AMR, and GMR sensors, which are significantly ahead of Hall sensors. Among MR sensors, TMR sensors are the most effective [102]. Unsurprisingly, the TMR sensor is also the most expensive. GMR sensors perform better than AMR sensors. Hall sensors have the lowest sensitivity and resolution; however, they make up for this by offering a high dynamic range at a low cost. Low cost, adequate performance and high availability make the Hall effect sensor the most popular magnetic field sensor on the market [103]. The challenges for these sensors are described in detail in [104,105]. Different structures of MR sensors are described in detail in [106] and schematically presented in Figure 10.

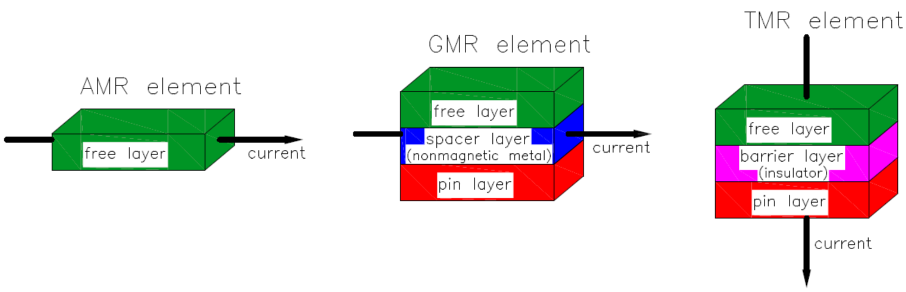


Figure 10. Different structures of MR sensors.

4.2.2. Optically Pumped Magnetometers

The article [107] presents a highly sensitive, miniature, scalar optical atomic magnetometer configured to operate in the Earth's magnetic field. Its operating principle is based on the optical pumping of caesium atoms undergoing Larmor precession in the presence of a magnetic field at a frequency proportional to the magnitude of the measured magnetic field. The two sensors can operate together without interference with a sensor distance of only 2.5 cm. Together with a sensitivity of 1 pT/Hz, this allows measurements of tiny signals from local sources in the presence of significant common magnetic field disturbances from distant sources. Measurements as diverse as the human heart's magnetic field and ferrous contaminants in food are now possible without the need for cryogenics or a specialized magnetic shielding environment. Optically pumped sensors use atoms as the magnetic sensing element. The magnetic field exerts a torque on the magnetic moment. Thus, atoms with a precession of magnetic moments in the presence of a magnetic field that have a frequency proportional to the magnitude of the magnetic field possess what is known as the Larmor frequency. Accurate measurements of the Larmor frequency of an ensemble of atoms provide a reliable measure of the magnitude of the magnetic field, which is largely insensitive to the orientation of the sensor in relation to the direction of the magnetic field. In thermal equilibrium, the magnetic moments or spins of individual atoms in the assembly are randomly oriented. The atomic spins must first be aligned with an optical pumping process using pump light to produce a macroscopic polarisation spin. This polarisation of the ensemble spin is then optically probed using probe light, with the intensity or polarisation modulated at the Larmor frequency depending on the detection scheme used. This method was first presented by Bell and Bloom in 1961 [107]. In [108], the authors compared measurements made with an optically pumped magnetometer and a sensor using SQUID technology. Very high correlations were seen, but this requires further research. The authors of [109] investigated the primary sources of error in optically pumped magnetometers with intense off-resonance pumping in the Earth's magnetic field. Nonlinear Zeeman splitting and magnetic orientation-dependent light shifting were the two leading causes. The theoretical analysis was confirmed experimentally, and the authors concluded that compensation coefficients must be developed.

5. Development Trends in Diagnostics

5.1. Signal Filtering

One of the most significant drawbacks of the measured signal is the high degree of noise. The authors of [110] proposed filtering based on wavelet decomposition. Experimental results showed that this analysis was practical with the Elman recognition network. The results obtained were quantitative, and it was difficult to decipher the nature of the damage from them. In [111], a wavelet filter algorithm based on ensemble empirical model decomposition (EEMD) was proposed with which system noise was effectively suppressed. Compared to the algorithm described in [112], the solution has the following advantages: higher computation speed, better filtering effect and high signal-to-noise ratio (SNR). The authors of this paper both located the wire rope defects and quantified them. This solution provides reliable evidence of the degree of wire rope damage, allowing criteria for the rope's decommissioning to be determined. To solve the diagnostic problems associated with signal analysis, such as the low defect recognition rate, poor signal denoising effect and long testing time, the authors of [113] proposed an algorithm combining a kernel extreme learning machine (KELM) with a compressed sensing wavelet (CSW). The article describes normalization, segmentation and positioning methods, effectively improving classification accuracy for cracked wires. However, this method does not recognize fatigue wear or the influence of corrosion cavities. The authors of [114] paid particular attention to the appropriate analysis of the obtained wire rope diagnostic signal. Eight different methods of de-noising and signal processing were proposed: low-pass, Butterworth, median and mean filtering; Gaussian and polynomial fitting; and wavelet and empirical mode decomposition (EMD). The best performance was shown by the Gaussian filtering method. Unfortunately, not enough different wire rope designs have been investigated, and this cannot be translated as a universal algorithm. The paper's authors emphasized that there is a need to combine different signal analysis methods, which requires further work and research. In [115], a prototype device based on measuring the residual magnetic field (RMF) components was designed. The authors proved that the proposed model was superior to traditional wire rope discontinuity detection methods due to its high accuracy and negligible sensor size. This paper proposed an algorithm based on Hilbert–Huang transform (HHT) wavelet filtering and compressed sensing (CS). Experimental results showed very high convergence of the damage indicated by the filtering with the actual damage. By using digital image processing, accuracy higher than 90% was achieved. However, the work needs to be improved. The authors ignored the direction of the damage at the perimeter of the rope. In engineering practice, this is extremely important, as damage distributed around the circumference of the rope is less threatening during operation than damage in the same direction. The work also does not consider the rope pitch: the spiral resulting from twisting the strands that make up the rope. An interesting approach is shown in [116]. This paper proposes a three-dimensional method for imaging inverted magnetic sources in a near field of unknown shape, position and magnetization. The method transforms the total anomalies of the observation surface into the sum of the field vector anomalies and then constructs a function to minimize the deviations between measured and predicted magnetic anomalies. The principle of magnetic dipole equivalence is used for the calculation. The Gauss–Newton and coupled gradient algorithms are used for the inversion optimization process. This method has been used to identify steel pipes but, for wire rope damage detection, its accuracy needs to be higher.

5.2. Intelligent and Quantitative Rope Inspection

In [117], a new visual method for detecting wire rope defects was proposed that combines the convolutional denoising autoencoder (CDAE) and IsolationForest (iForest). Previous methods have focused on the manual analysis of defects; the classifier constructed in this study allows this process to be automated. Unfortunately, there are limitations for the applicability of this algorithm relating to vibrations, grease, dust and different light intensities. An even more complicated limitation is the need to prepare a sufficient number of Dan defects to train the system. An obvious limitation that disqualifies the above algorithm is the fact that it can only be applied to the outer layer of wire rope wires. Ref. [118] describes a template for segmenting wire rope surface defects. The method proposed can adapt well to the surfaces of test objects and, in contrast to previous work, does not require any defect samples. As in previous work, only defects in the rope's outer layer can be detected with this method. The authors of [119] focused on the quantitative diagnosis of discontinuities. Instead of a traditional Hall sensor array, they used a magnetic concentrator, which allowed for comprehensive data collection. Experimental tests were carried out for discontinuities ranging from one to five wires. The analysis of the results needs to be more conclusive, and additional studies are required to implement the proposed method successfully. Although the processing of the Hall sensor signal is complicated, the signal can contain more information than a magnetic concentration sensor. Using information fusion methods [120], deep learning [121,122] and multisensor Hall array signals, the sensor can be helpful for fault location recognition. It is vital to develop a fault recognition model for processing faulty signals from two sensors in further research. The article [123] focuses on the analysis of the tensile and bending stresses of a wire rope. The experimental results and the finite element methods show that the numerical model presented in the article can reflect the failure process in steel wire rope slings. Finally, the fracture in the steel wire rope sling was photographed using an electron microscope.

6. Conclusions

This article comprehensively systematized the knowledge about wire rope diagnostics. Using brief descriptions, important studies on wire rope operations were listed. Rope degradation mechanisms and the characteristics of diagnostic methods were described in detail. A new division of magnetic rope diagnostic methods into active and passive methods was presented. Development trends in filtering the received signal were also described, and the future of intelligent systems was analysed. As a conclusion to this paper, several observations automatically emerge:

1. The development of wire rope diagnostics is an issue of great importance for the safety of people using wire rope transport equipment;
2. There are many methods of wire rope diagnosis: magnetic flux leakage (MFL), eddy current testing (ECT), acoustic emission (AE), ultrasonic guided waves (UGWs), radiography and vision testing. Each method uses different physical phenomena, and intensive research is being conducted on almost every method;
3. It is crucial in the context of wire rope diagnostics to understand the mechanisms of degradation. These mechanisms are closely related to the physical phenomena that accompany them;
4. It is impossible to indicate a single effective method for wire rope diagnosis. The characteristics—advantages and disadvantages—of each method presented here demonstrate that, for a comprehensive analysis, testing must be carried out using various methods. Of all the methods presented and described in detail, magnetic methods using the phenomenon of magnetic flux leakage are the most prevalent;
5. The most intensive research is currently being conducted on passive magnetic methods using the self-magnetic flux leakage (SMFL) phenomenon;
6. The selection of a suitable test method for a particular defect in a wire rope must be accompanied by the selection of a suitable sensor in terms of its operating mechanism and measuring range;
7. The resulting diagnostic test signal must be appropriately filtered to assess the true extent of damage to the test object;
8. In parallel with the development of passive magnetic methods, intelligent techniques are needed to assist in assessing the technical conditions of steel wire ropes;
9. Safe steel-wire-rope working environments and a comprehensive inspection programme are essential for future practical applications.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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