ORGANIZZAZIONE INTERNAZIONALE TRASPORTI A FUNE
INTERNATIONALE ORGANISATION FÜR DAS SEILBAHNWESEN
ORGANISATION INTERNATIONALE DES TRANSPORTS A CABLES
INTERNATIONAL ORGANIZATION FOR TRANSPORTATION BY ROPE
ORGANISACION INTERNATIONAL DES TRANSPORTES POR CABLE

Recommandations techniques en vigueur

BOOK-3-1
Replaces the book n° 3
(Published in September 2015)

SURVEY OF MAGNETIC ROPE TESTING OF STEEL WIRE ROPES


Compiled between September 2011 and February 2015
by the O.I.T.A.F. Work-Committee No II

La présente recommandation n'est pas d'application obligatoire, mais constitue un document de travail mis á disposition de la profession.
Il serait souhaitable d'appliquer dans tous les pays, sous réserve de normes nationales et dispositions administratives chi prévvvalent.

Table of contents

Contributors*: by alphabetic order*

Urs Amiet (OFT, CH), Peter Baldinger (Chairman) (Teufelberger Seil GmbH, Wels, AT), Rudolf Beha (LEITNER AG, IT), George Boyden (SANDIA PEAK TRAM CO, USA), Andrea Collina (POLITECNICO DI MILANO, IT), Stéphane Contardo (STRMTG, St. Martin d'Heres, FR), Bernhard Hinterndorfer (TU-WIEN, A), Peter Huber VDS (Zugspitzbahn AG, Garmisch, DE), Georg Kopanakis (Consultant, Koblenz, CH), Konstantin Kuehner (IFT STUTTGART, DE), Bruno Longatti (FATZER AG, CH), Hans Machalik (BMVIT, A), Christophe Martinet (ST-HILAIRE ROPEWAY, FR), Stefan Messmer (IWT, CH), Federico Paglia (Redaelli Tecna S.p.A., Brescia, IT), Stephane Pernot (LETSCAN, FR), Renzo Pesciallo (SBS, Bern, CH), Josef Sutter (Doppelmayr Seilbahnen GmbH, Wolfurt, AT), Sven Winter (IFT STUTTGART, DE).

Introduction

Summary: *The original OITAF book n°3 – a historical document about magnetic rope testing dating from 1965 – soon seemed to become outdated and therefore needed to be reviewed completely, to present the state-of-the-art in non-destructive testing (NDT) used to assess the safety of ropes for ropeways and cable car facilities.*

Magnetic rope testing (MRT): *Non-destructive magnetic rope testing is the use of either electromagnetic or permanent magnetic equipment using magnetic-flux and/or magnetic flux leakage principles. It is capable of detecting discontinuities and/or changes in metallic cross-sectional area in ferromagnetic wire ropes and cables.*

1.1 Context and scope

This booklet has been written for ropeway operators, rope and ropeway manufacturers, as well as rope inspection companies, splicers, and more generally for the large community of people interested in ropes, including ropeway or cable car owners, operators, rope professionals, authorities, academics, etc.

Suppose we take a poll asking simple questions of wire rope professionals such as:

- what do you feel about magnetic rope testing ?
- what is your actual understanding of MRT ?
- how far do you trust MRT results ?

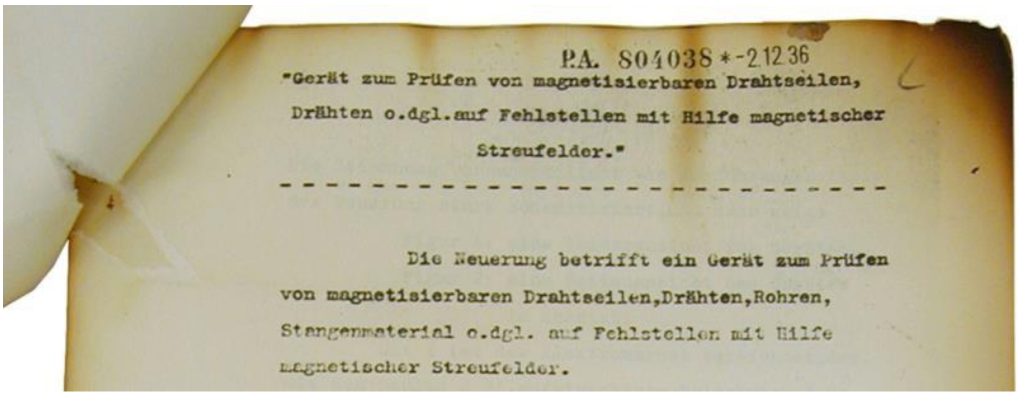
Most answers would probably fall near these two opposite extremes:
"...MRT does not work, I don't believe in it! ..."
"...I know nothing about MRT but it works perfectly, MRT can detect all rope faults and can replace any other rope inspection methods! ..."

This booklet is also intended to fill the gap living between the first simple rejection and the second blind faith by providing explanations of the magneto-inductive principle and its implementation in state-of-the-art MRT device technology, and sharing knowledge learned through their daily work by experienced rope inspectors and research institutes.

Our main goal will be achieved when everyone getting to the end of this document is able to establish a clear position between these two confusing and erroneous statements.

1.2 Historical overview

The development of rope monitoring devices seems to originate – like the wire rope itself - in the mining industry. Basic electric circuits provided warning signals as protruding wire-breaks caused an earth leakage in the system by touching a bare conductive loop placed around the rope. While magneto-inductive inspection was introduced to inspect gun barrels in England at the beginning of the twentieth century, the South Africans McCann and Colson [1] described the magnetic testing of wire ropes for the first time in 1906.
In 1931 Richard Woernle started research in the field of magnetic rope testing at the University of Stuttgart in Germany. The first patent application for an opening measuring coil system suitable for inspecting wire ropes in situ was made by Woernle and Müller [2] in 1937 as illustrated in Figure *1*.



P.A. 804038 *-2.12.36

"Gerät zum Prüfen von magnetisierbaren Drahtseilen, Drähten o.dgl. auf Fehlstellen mit Hilfe magnetischer Streufelder."

- -

Die Neuerung betrifft ein Gerät zum Prüfen von magnetisierbaren Drahtseilen, Drähten, Rohren, Stangenmaterial o.dgl. auf Fehlstellen mit Hilfe magnetischer Streufelder.

Figure *1*: Patent of Woernle and Müller, University of Stuttgart, from December 1937.

All the early systems, like those depicted in Figure *2* and Figure *3*, were excited electrically, usually by direct current. The output signal was printed on-line by an x-y chart-recorder.

Figure *2*: DC excited rope inspection on an ancient Bleichert jig-back, Zugspitze 1950s.

Figure *3*: Professor Hugo Müller supervising an x-y chart recorder, Zugspitze 1960s.

After the Second World War, some more or less standardized inspection systems were considered by the inspection authorities of several countries for the inspection of both mine hoisting ropes and the ropes of the new passenger-carrying cable car industry. At that time mostly only the pioneer aerial tramways from the 1920s and 1930s were still in operation, while regulations for magnetic inspection of cable car ropes were barely in existence.
A first Swiss inspection device [3] developed by SIGNUM, Wallisellen, was used in March 1938 to inspect the haulage rope of the Dolder funicular in Zurich.
One of the first magnetic inspection tasks described in France was monitoring dam construction ropeways using a system designed by André Halec.
Poland applied their first magnetic inspections to the Bleichert trams on Kasprowy Wierch in Zakopane in 1947. Notably magnetic tests became mandatory for all Polish passenger ropeways in 1972.
Italy’s CSIF testing institution was established in Rome in the 1950s by the Ministry of Transportation. Since 1993, the tasks of the former CSIF have been shared by LATIF (founded in 1971 in Trento) and the NDT Lab at Trieste University (which has been operating in the MRT field since 1957).
In the 1960s a standardized electromagnetic system was developed in Switzerland, named Integra [3] shown on Figure *4*. Integra has also been used as a basis for reference for other magnetic systems in several countries.

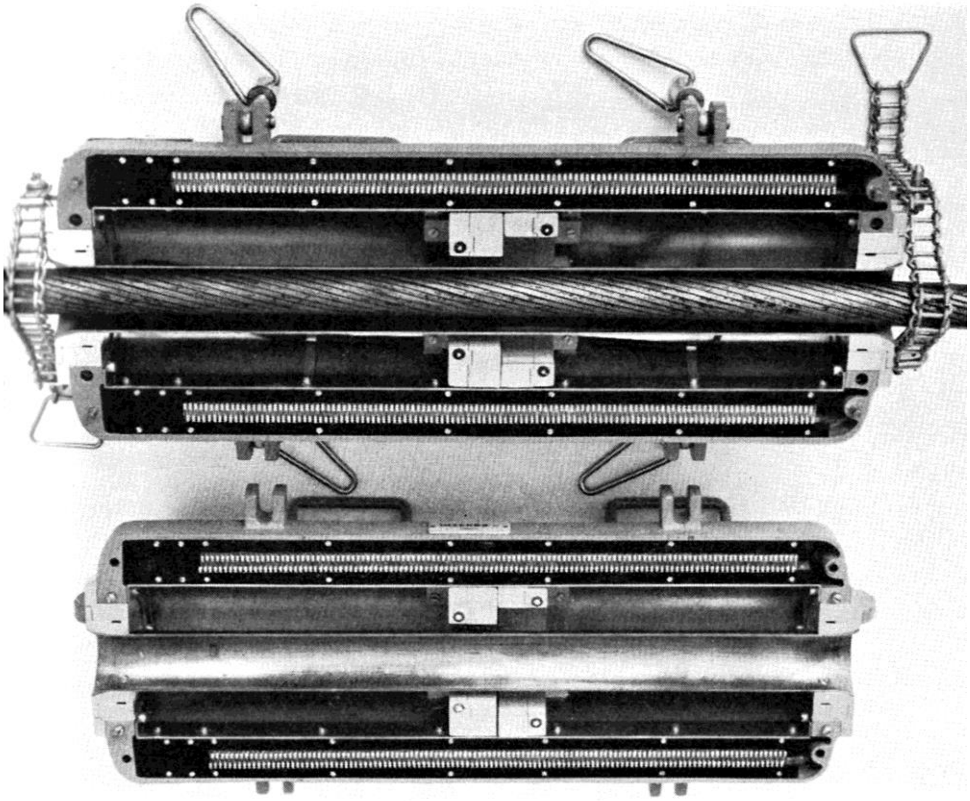


Figure *4*: Integra d.c. system from 1956.

By the 1970s efforts to make magnetic testing simpler resulted in the use of permanent magnets, as implemented in the Kündig testing device.
Roughly starting around 1990, ferritic magnets have been replaced by magnets employing rare earth materials. Such magnets are more powerful for the same size and weight, and retain their magnetic strength much better. Both the weight and the size of the testing devices could be reduced considerably. As a result of the rapidly improving capability of digital systems, computer-based recording units are state-of-the-art today. But there is still a variety of both analogue and digital chart recorders in use all over the world.
The first modern use of Hall-effect sensors as a means for detection of rope faults was reported at the OIPEEC Round Table in Krakow by Stachurski [4] in 1981. Later, these sensors were implemented to measure the loss of metallic area (LMA) associated with smoothly tapered sections which are reliably detected by signals from coil based sensors. The reader is strongly invited to read publications from Chaplin et al [5] and Dohm [6] for a thorough understanding of LMA based technology of magnetic rope testing.
In the mid-1990s, IFT University of Stuttgart constructed a high resolution measuring device using a large number of Hall sensors in a circular array around the rope: this system is able to provide a greater detail of information on the position and the depth of defects within a rope [7]. A very similar system was developed by EMPA, Switzerland [8] at the same time.

As larger ropes are being used both in aerial ropeways and in applications such as the offshore industry, magnet systems must increase in strength to cope with the increase in metallic cross section. In addition, system designers must continue to improve procedures for management and processing of the data obtained from rope inspections, including automated interpretation and processing for further diagnosis. In this way the operators of high performance ropeways, like airport transport systems or urban tram lines, will be provided with more and more support in assuring the reliability of their systems.

1.3 Limits of application

This booklet gives an insight to non-destructive techniques that enable inspection of the surface of a rope or its internal structure. It is not intended to be either an instruction manual or a normative document. The aim is to provide general understanding about rope NDT methods, leading to complementary explanations as an addition to normative documents, safety warnings, operational guidelines and descriptions of examples from experience.

In the booklet, "rope" refers to steel wire ropes used in ropeways, such as:

- hauling ropes,
- carrying-hauling ropes,
- carrying ropes,
- tension ropes.

Under no circumstances, should this book:

- be used as a reference manual for performing MRT tests,
- replace normative rules / standards.

The main purpose is to highlight the importance and subtleties of the magnetic rope testing method for assessing the safety of rope operating conditions.

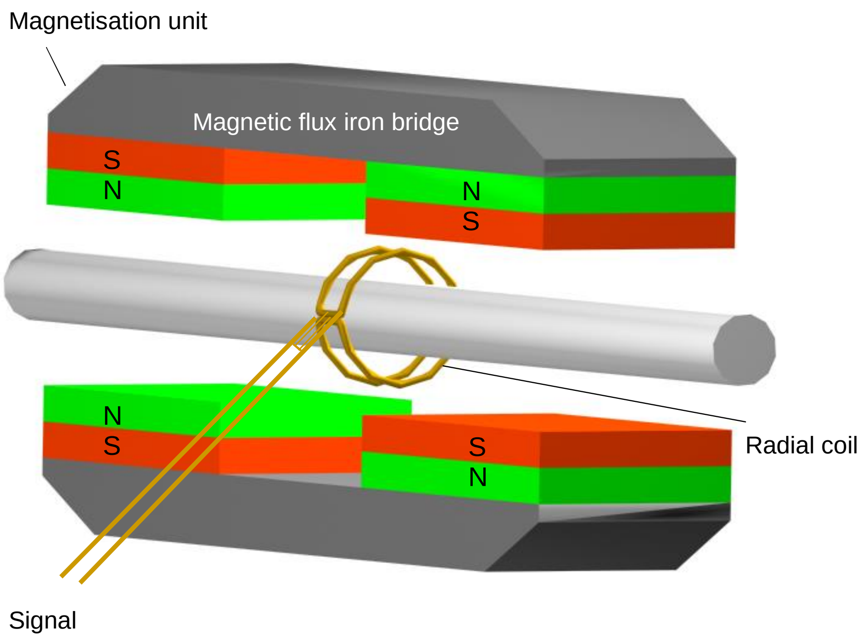
1.4 Book outline

After reviewing the background of magnetic induction theory and related magnetic rope testing principles in Section 2, the booklet introduces in Section 3 general features of modern MRT devices and their sensing elements. In Section 4, the set-up of MRT devices on cableway ropes is thoroughly described in relation to the specific rope use – carrying, carrying-hauling or hauling ropes. Guidelines are discussed, and illustrated by examples, on the correct performance of MRT tests. Section 5 and 6 introduce the basis of signal processing operations developed to detect rope defects by analyzing measuring coil signals. Rope discard criteria commonly used in standards are introduced in Section 7 and their philosophy is explained. Hazards frequently encountered during MRT tests are discussed in Section 8. Personnel requirements and safety recommendations to minimize the risk of staff injury are also provided. Finally conclusions and the prospects for magnetic rope testing are given in Section 9.

***Summary**: The concept of magnetic induction is derived from the Lenz-Faraday law of physics which is thus the underlying theory of MRT. The method consists in first exciting a rope longitudinally by means of a d.c. coil or permanent magnets, and secondly in monitoring the magnetic flux leakage associated with the gap between the adjacent ends of a broken wire. In practice, flux leakages induce a voltage across a measuring coil. This Section introduces the radial or axial coil strategies commonly used in MRT devices and the resulting wire break signals related to various arrangements. Finally the issue of the rope ground signal confusing the identification of wire breaks from MRT signals is explained, and the role of wear and corrosion on MRT signal form is introduced at an advanced level.*

1.5 Measuring principle

If a wire rope is magnetized along its axis, disturbances in the structure, such as wire breaks, cause a leakage field. Changes in the radial or axial leakage field component induce a voltage in an induction coil enclosing this changing field. The resulting analogue voltage is amplified electronically and, normally, converted into a digital signal before it is recorded on paper or stored in memory. The measuring principle of magnetic leakage field-testing is shown in Figure 5.



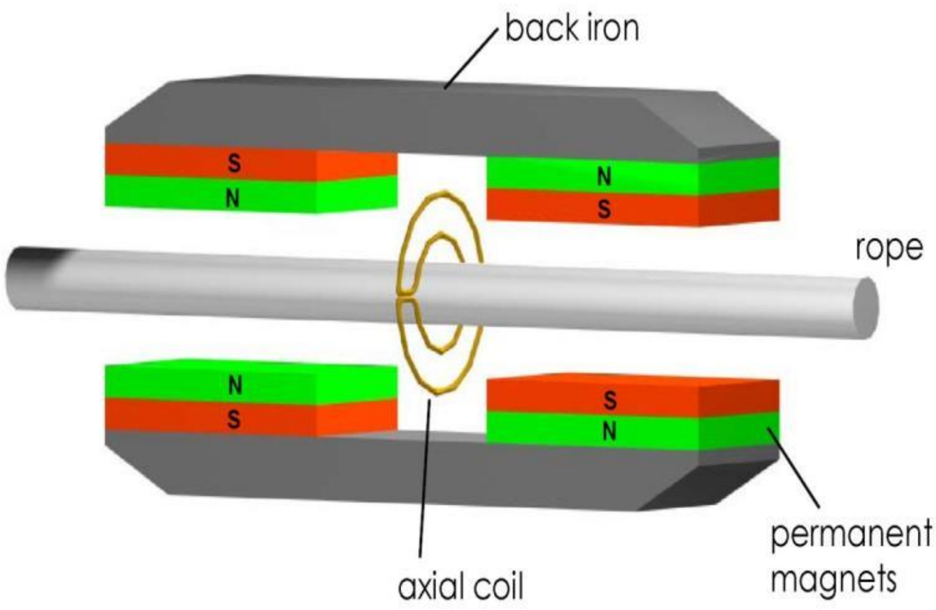


Figure 5: Measuring principle of magnetic leakage field test : upper - radial coil, lower - axial coil.

In order to enclose all of the rope, two radial coils are needed, each one enclosing one half of the rope. If not specifically stated all discussion below relates to the radial arrangement of the coils only.

1.6 Magnetization

With a rope in place an MRT system establishes a magnetic circuit which needs to magnetize the metallic cross section of the rope up to its saturation level of 2.1 Tesla for steel wire. A strong and homogenous magnetization of the rope cross-section in the monitored zone is necessary to obtain a high defect detection rate over the whole rope cross-section, especially to detect reliably wire breaks in the rope interior. The magnetic and mechanical dimensions of the MRT device have to be chosen so that a variety of defects can be interpreted optimally within the range of rope diameters which are to be inspected with the device.

Back-irons are usually installed to close the magnetic circuit parallel to the rope axis on the outside. Excitation can be carried out by permanent magnets or direct current coils. Excitation using a.c. never became established for ropeway application (although it was the preferred technology for mine hoisting ropes in South Africa for many years) as it requires low frequencies of only a few Hertz. One problem with a.c. excitation is that self-induction makes the complete reversal of the magnetic field slow which in turn leads to a skin-effect magnetic penetration of the rope. Devices currently in use have various arrangements of magnetizing units. Table 1 gives an overview of typical arrangements (hatched elements represent magnetic parts):

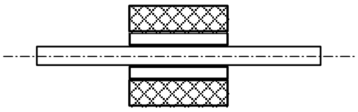
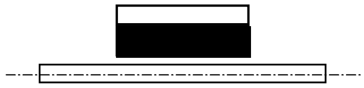
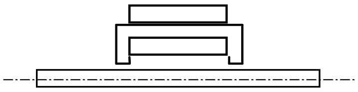
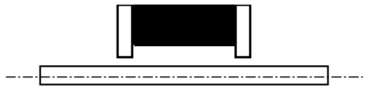
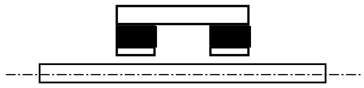
	Electric magnet	**Permanent magnet**
main circuit arrangement		
shunt arrangement		 

Table 1: Arrangements of magnetizing units.

The magnetic field of a typical shunt arrangement using permanent magnets is show in Figure *6*:

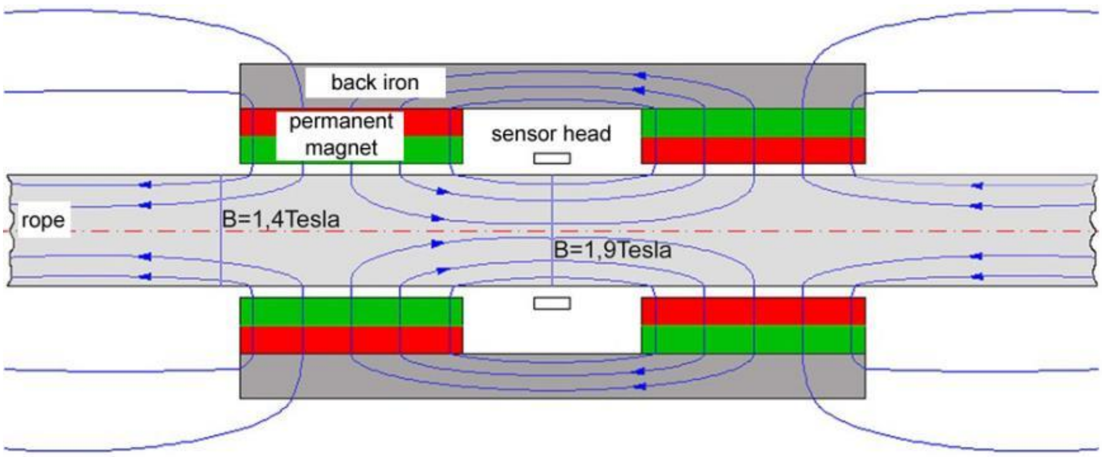


Figure *6*: Magnetic field of a typical permanent magnet device.

1.7 Rope ground signal (envelope or signature)

The MRT device magnetizes the rope by means of a magnetic field that is essentially parallel to the rope axis. The direction of the magnetic field generated in the rope is broadly influenced by the helix or double helix of the wires as well of the overall construction of the rope and the device itself.

In addition if the wires or strands are compacted, that will also have an influence. The magnetic field therefore continuously bridges the "wire barriers" and forms a magnetic dispersion that is evident in the leakage field. This magnetic dispersion induces the so-called rope ground signal, or envelope, in the measurement coil. The "undisturbed" leakage field (no wire breaks, no inter-wire nicking or indentations or other changes in cross-section) therefore represents the structure of the rope itself and is, in the ideal case (constant lay

length), a periodic function. Essentially the ground signal is generated by the helical nature of geometry of the wires and strands.
The amplitude of the ground signal decreases in the initial stages of the lifetime of a rope as the rope beds in. After this, the ground signal becomes higher with increasing use because of wear, inter-wire nicking, local deformation (causing changes in steel permeability) and corrosion. Generally speaking, the ground signal can vary considerably, and mostly depends on rope design, rope manufacture and the MRT device used to inspect the rope.

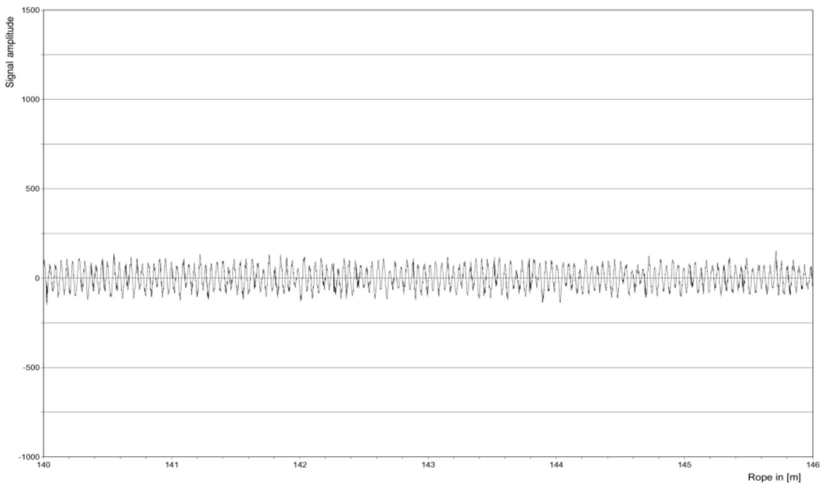


Figure *7*: Example of ground signal of a new stranded rope.

In the case of new ropes it should be noted that the ground signal of compacted wire ropes could be higher, and of locked coil ropes could be lower, than the ground signal of common round wire stranded ropes. Figure *7* shows the basic ground signal of a new rope.

1.8 Wire break indications

A basic understanding of the relationship between a wire defect and the measured signal is shown by the basic formula of the law of induction:

$$U_i = -N \cdot \frac{\Delta(B \cdot A)}{\Delta t} \qquad (1)$$

The inductive voltage U_i in formula (1) is function of:
- the effective area *A* seen by the coil,
- the number of turns *N* of the coil (a fixed parameter for the test),
- the rate of change $\Delta B/\Delta t$ of the magnetic field *B* which is determined by the shape of the wire break and its gap length.

The shape of the wire itself is a fixed parameter and cannot be changed. But the distinctiveness of a wire break signal is, amongst other things, related to the design of the sensor unit and the working excitation as well as the relative speed the inspector chooses. If the test is performed too slowly, the wire break signals will not rise sufficiently in the measured trace. But if the speed chosen is too fast, vibrations and a shift of the inner field centre can cause a loss of signal quality.

The wire break signal is seen in the typical "w" shape, which is created by the combination of the single inductive signals U_1 and U_2 of the two break ends of the wire defect into the composite signal U (see Figure *8*).

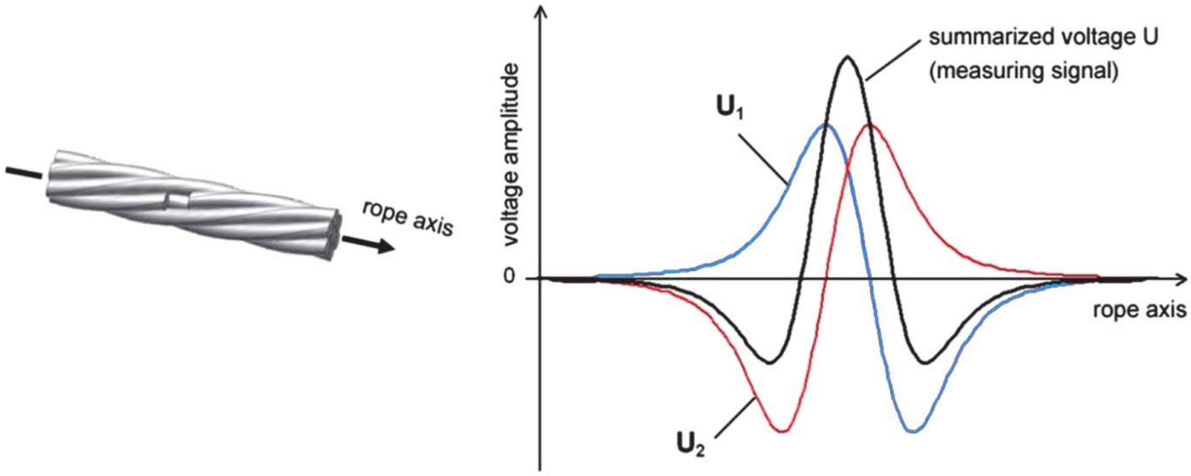


Figure *8*: Combination of break-end signals into overall defect signal
(for simplicity the rope is shown schematically as a single strand)

The shape of the w-form varies according to the length of the wire break air gap (see Table 2). In the case of small air gaps the signal amplitude is low, it increases as the gap becomes larger and then reaches a maximum. As the air gap becomes still larger, the signal amplitude decreases again and begins to lose its typical shape. This can first be seen in the shape of a dip. As the gap becomes bigger, so does the dip and in the case of very large gaps reaches the zero line asymptotically, so that the original signal amplitude is divided into two individual signal amplitudes. These two signal amplitudes U_1 and U_2 (see Figure *8*) correspond to the two wire ends of the wire break but have opposite polarity.

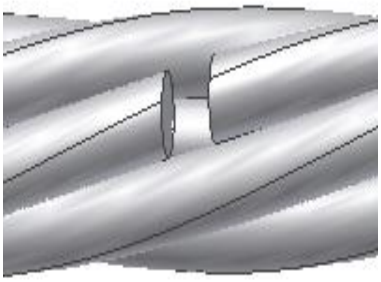
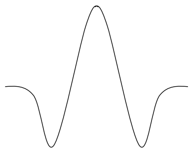
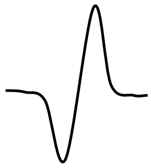
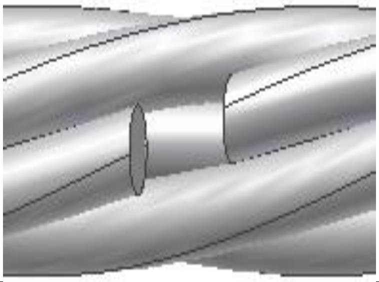
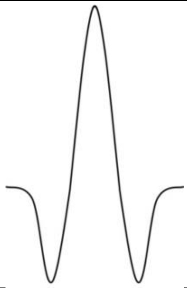
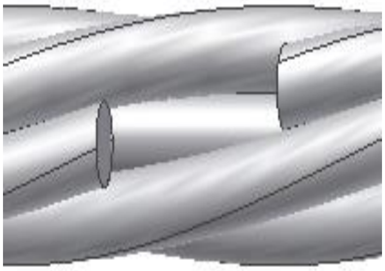
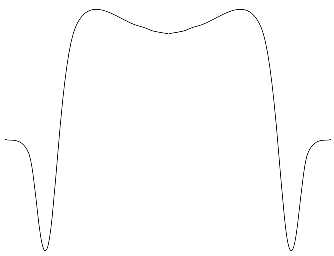
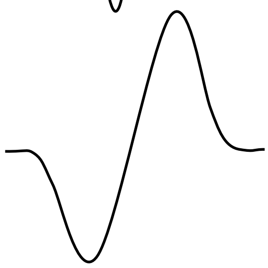
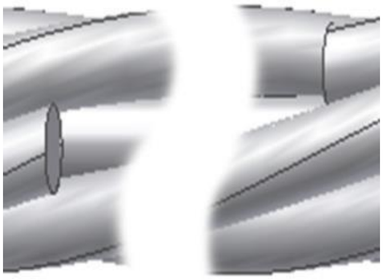
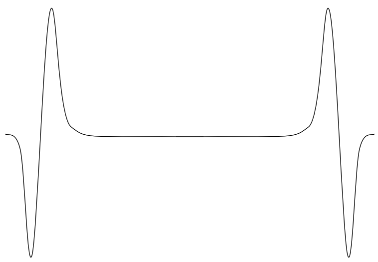
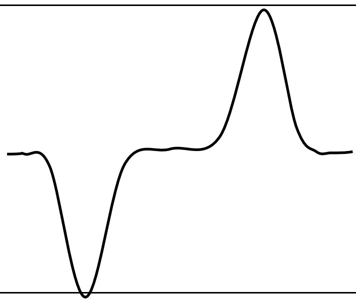
defect length	***signal of a radial coil***	***signal of an axial coil***
		
		
		
		

Table 2: Wire-breaks and typical corresponding leakage field of both radial and axial signals.

The phenomenon of wire break clusters will be described later in Section 5. The leakage field shown above corresponding to a broken wire is proportional to the cross-sectional area of the wire. Thicker broken wires can therefore cause a greater deflection in the measuring signal than thinner wires. Apart from the variables already listed which influence the signal (such as the strength of the magnetic field, the length of the gap, overlapping of defects and the amount by which the cross-section is reduced), the quality of the measurement also depends on the position of the defect within the cross-section (central or surface), the type of defect and the geometry of the test coil. If a broken wire has no gap, the height of the signal is zero. The selected magnetization and the arrangement of the coils need to ensure that thin broken wires with small air gaps can be detected and recorded reliably.

1.9 Relative Signal Density

It is possible to create a diagram of the relative signal density in specific rope sections or the whole length. The amplitudes, both positive and negative, of the measured peaks are compared to their (relative) quantity over the whole measurement, which leads to a bell-shaped curve. If a rope is new, the signal is dominated by the large proportion of low amplitude peaks and thus the bell-curve shows a high centre and a tight envelope. As a result of wear and corrosion, the bell-curve widens and becomes flatter, because there is an increasing number of higher peaks in the measured signal (see Figure *9*).

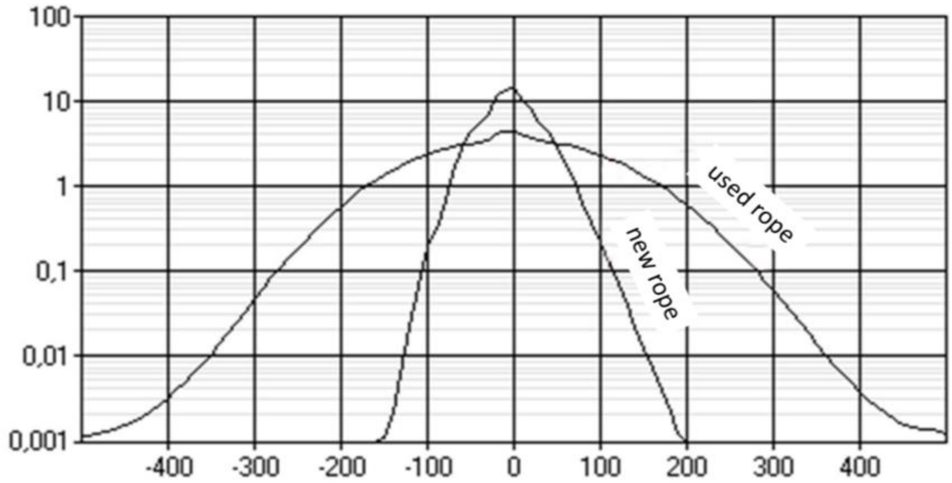


Figure *9*: Change in bell-curve of relative signal density from wear and corrosion.

A particular case is shown on Figure *10*. If there is a large number of wire break signals in the measurement, there is a corresponding number of high positive signals which show up above the ground signal envelope. So the bell-curve becomes asymmetric and shows a small foot at its right hand end caused by wire-breaks.

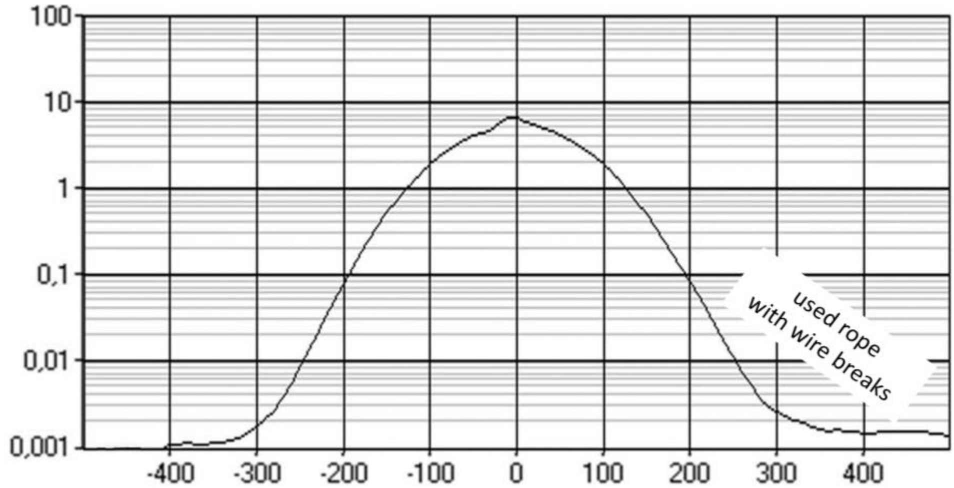


Figure *10*: Bell-curve with an asymmetric foot caused by wire-breaks.

2 MRT Devices and Sensor Technology

***Summary**: The design and features of MRT devices are of great importance in ensuring that the induced magnetic field will saturate the central part of the rope cross section, and is fairly homogeneous in the vicinity of the measuring coils. This Section describes some typical shapes of MRT devices and measuring coil technologies, and guidelines are given for designing effective MRT devices. Key concepts for signal calibration are also given to assess MRT device designs in the laboratory. Magneto-inductive simulation and a high resolution 3D device, using a belt of Hall sensors, are finally introduced for advanced readers as prospective technology to provide a better understanding of rope defect distributions.*

2.1 Typical shapes of test devices

Over the history of MRT device development, several classic shapes have been adopted by different manufacturers, which all consist of the same basic components:

- main frame,
- bars, tube or casing carrying the excitation source of magnets and back-iron,
- sensor heads,
- centring elements, like rollers or guide blocks,
- connection box for coil channels, with optional signal pre-conditioner,
- triggering and distance measuring device,
- external features like handles, lift-off levers, cable anchorages, etc.

The total arrangement depends on how the magnets themselves are set up in the system, while the magnetic bar is often configured as a kind of modular component. There are various designs existing around the world, so the following descriptions will only give an overview of established European magnetic circuit designs.

2.1.1 U-Shape (asymmetric excitation)

The main advantage of a u-shape shown in Figure *11* is that the system provides physical clearance on one side, which is typically the lower side. Magnetic excitation is designed to be capable of saturating the whole cross section, although with the magnetic bars only installed in a triple arrangement, the magnetic strength has to be somewhat oversized in relation to the maximum rope cross-section for which the device is designed. This shape allows the system to run over slack carriers and tower saddles for track rope inspections, which minimizes the ropeway downtime for inspection purposes. Only the lower half of the sensor head can be folded away. As the saddles of modern aerial tramways which do not have carrier brakes are wider compared to those of conventional trams – sometimes the ropes are also clamped on the tower – it may be necessary to use an automated lift-off device to move the device and its delicate sensor heads away from the rope. Due to the heavy weight of the complete U-shaped system for very big locked-coil ropes, systems like this are generally used only for ropes with diameters greater than 100mm.

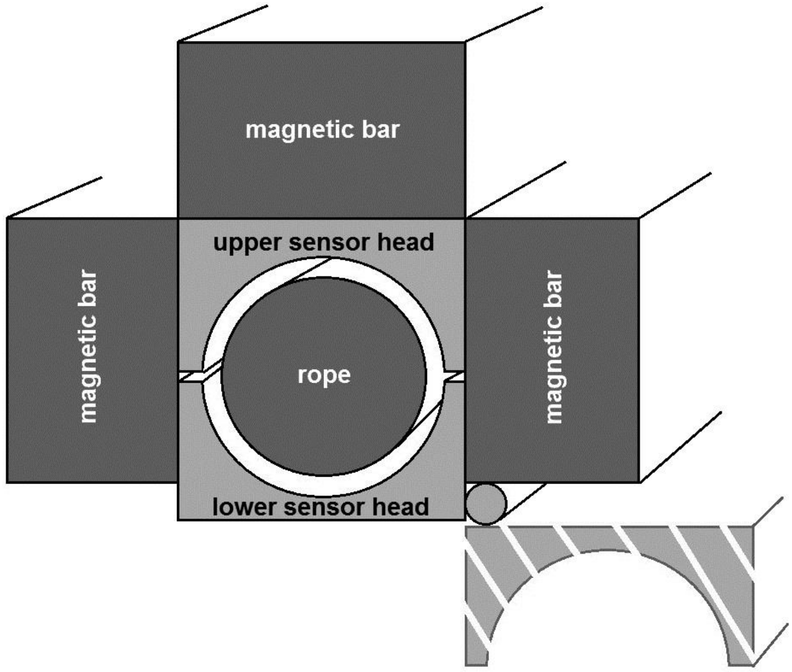


Figure *11*: Typical U-shape magnetic testing device.

2.1.2 Separable Design – two-shell system

Separable designs as in Figure *12* typically use a symmetric excitation of the rope, which leads to the most economic excitation in respect to the maximum metallic cross section for which they are designed. The system can be separated into two – usually symmetric – parts for installation and removal. The opening and closing process can be manual or automated. Those designs made for smaller cross-sections can be operated manually as the magnetic forces can be handled safely by a single human operator. For larger sizes there needs to be an automated system.

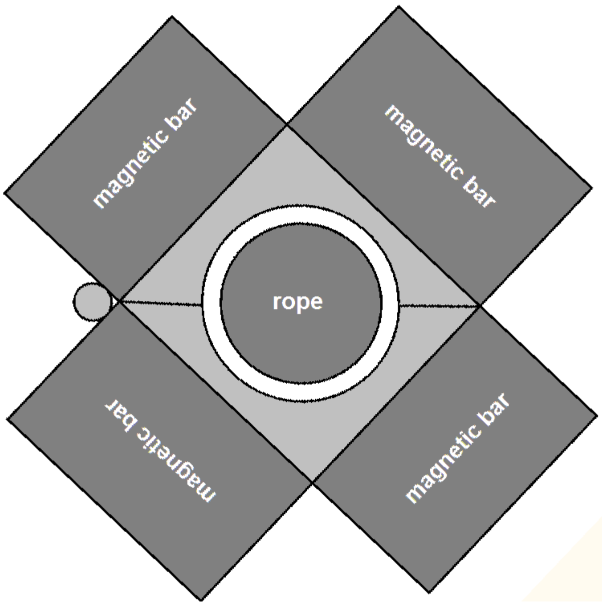


Figure *12*: Typical two-shell magnetic testing device.

2.1.3 Separable Design – modular bar system

Another type of separable system shown in Figure *13* is designed for inspecting ropes with extremely large cross sections. Systems are available for ropes up to 140mm in diameter. The magnetic excitation of very large offshore crane ropes, and suspension or track ropes, leads to heavy magnet elements and extremely large forces, which cannot be handled safely on-site. For this reason, a light weight, non-magnetic frame, with integrated sensor heads, is first installed around the rope. Then, individual bar magnets are mounted on the frame.

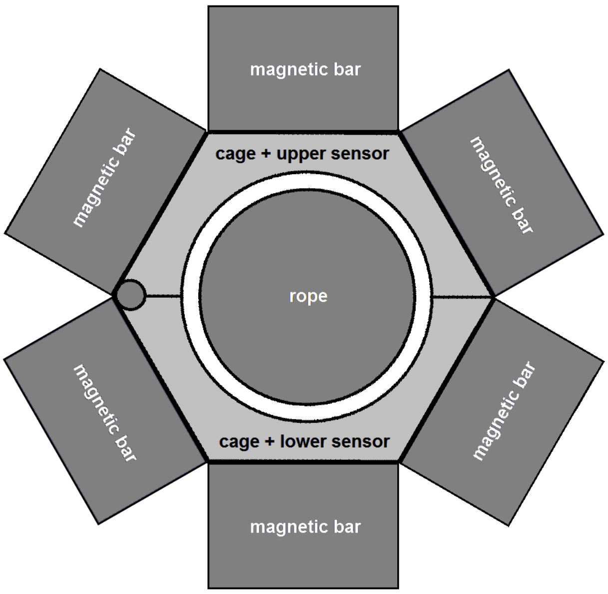


Figure *13*: Typical magnetic testing device with individual, detachable magnets.

2.1.4 Electric d.c. Excitation

Excitation using d.c. was the technology initially used for magnetic rope inspection. This technology is now being re-introduced because rope cross sections in bridge construction and the offshore industry are becoming so large that permanent magnet solutions are not feasible. Electric excitation can be provided by solid separable coil elements as used in the Integra system (see Historical Overview, §1.2). For larger devices a copper wire must be wrapped around the rope. In addition a portable d.c. energy source is required. Comparisons showed that the quality of the resulting measurements can be noticeably better with electromagnetic coils than with permanent magnet excitation.

2.2 Field-Calibration / Magnetic Flux Density

Calibration of the capability of a test device is described in the annex of the standard EN 12927. Over an axial length of ½ of its given maximum rope diameter, d_{max}, the magnetizing unit must be able to create a magnetic flux density B between 1.9 and 2.3 Tesla, measured in a coil surrounding a rope (or a metallic test piece for reasons of calibration) of the maximum metallic cross section A_{max} for which the unit was designed (see Figure *14*). Within this range the smallest rope which is specified for testing with the same unit shall not have a cross sectional area less than $A = A_{max} / 4$. Otherwise it must be demonstrated by measurement that the magnetic flux density does not exceed 2.4 Tesla in the small rope.

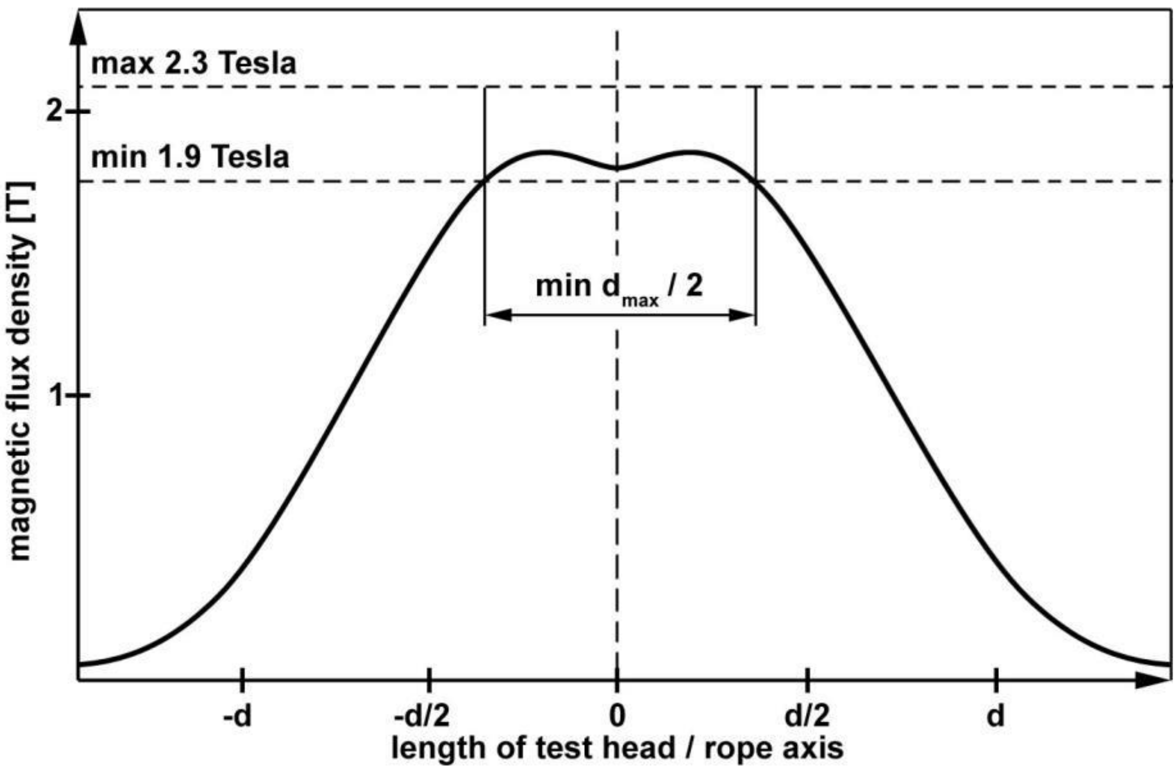


Figure *14*: Calibration curve for magnetic flux density required by EN 12927.

2.3 Sensors

2.3.1 Coils

Coil sensor heads are made of very thin copper wire of only a few micrometres thickness, wound in several hundred turns to create a half coil unit. The inside coil diameter should be as close as possible to the rope diameter with due allowance for operational vibrations, possible thickening or splice knots in stranded ropes. The Lenz-Faraday law of induction (1) requires that to generate a signal the coil needs a change over time of its active area, the magnetic flux density, or the metallic cross section of the test item. In effect this means the coil needs a relative movement of a defect through the test head at sufficient speed to create a measurable changing leakage field. A static measurement is not possible using a coil sensor head. Basically two designs of coils exist which are described in the following paragraphs.

2.3.1.1 Radial coil

Radial coils provide an active loop wrapped around the rope surface, which makes them sensitive to the variation of the magnetic field components which spread from the rope in the radial direction. If the test head is equipped solely with radial coils there are typically two different channels generated by coils of different widths.

The wider coil, typically more than 10mm wide, is usually designated as the main channel as it is more sensitive to wire breaks, corrosion and surface defects. It creates a smooth, but distinctive measuring signal and is less sensitive to light vibrations or minimal distortions.

The channel from the narrower coil, of only a few millimetres width, is usually taken as a back-up channel which is more sensitive, to wire break clusters for example. It can also create more distinctive signals of wire breaks which only have a very small air gap.

2.3.1.2 Axial coil

Axial coils provide an active loop in a plane normal to the rope axis, which makes them sensitive to the variation of the magnetic field components which spread from the rope in an axial direction. This coil arrangement, which is seldom used in MRT devices used for ropeway inspections, is not thoroughly detailed in this booklet.

2.3.2 Hall effect sensor

In contrast to coils, Hall effect sensors can measure magnetic field strength in a static mode as they are not based on the inductive law, but on the Lorentz-force acting across the sensor (see Figure *15*). Because the Hall effect sensor measures the magnetic flux density B directly, it can also measure tapered, smoothly changing sections of a rope, designated LMA (loss of metallic area) measurement.

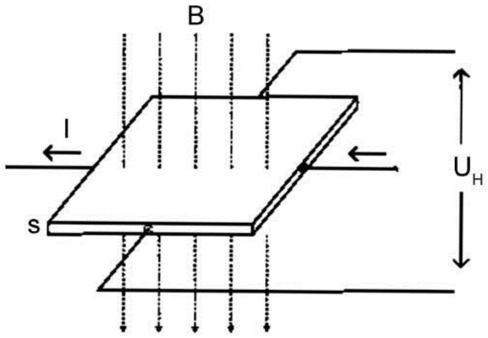


Figure *15*: Schematic representation of a Hall effect sensor.

The response of a Hall effect sensor is given by the formula (2):

$$U_H = R_H \cdot \frac{I \cdot B}{s} \qquad (2)$$

where:

U_H – Hall - output voltage
R_H – Resistance of Hall Sensor
I – intensity of current
s – thickness of conductor
B – magnetic flux density (the only changing parameter in the input)

Hall effect sensors are available with different sensitivities expressed in millivolt per Gauss (where 1 Tesla = 10,000 Gauss). The signals of several Hall effect sensors arranged evenly around the rope can be converted to a conventional 2D-curve which shows the same typical defect signals as the coil based sensors.

2.4 High-resolution Magnetic Rope Testing

In 1999, Nussbaum described in his PhD thesis [7] a method for calculating the 3D field associated with defects in a wire rope. This provided the motivation for the development of a system capable of measuring the 3D leakage field due to wire breaks, in order to verify the calculations. The development resulted in a sensor head carrying a ring of Hall effect sensors which are evenly arranged around the rope circumference as seen in Figure *16*. The system was called a high-resolution magnetic rope testing.

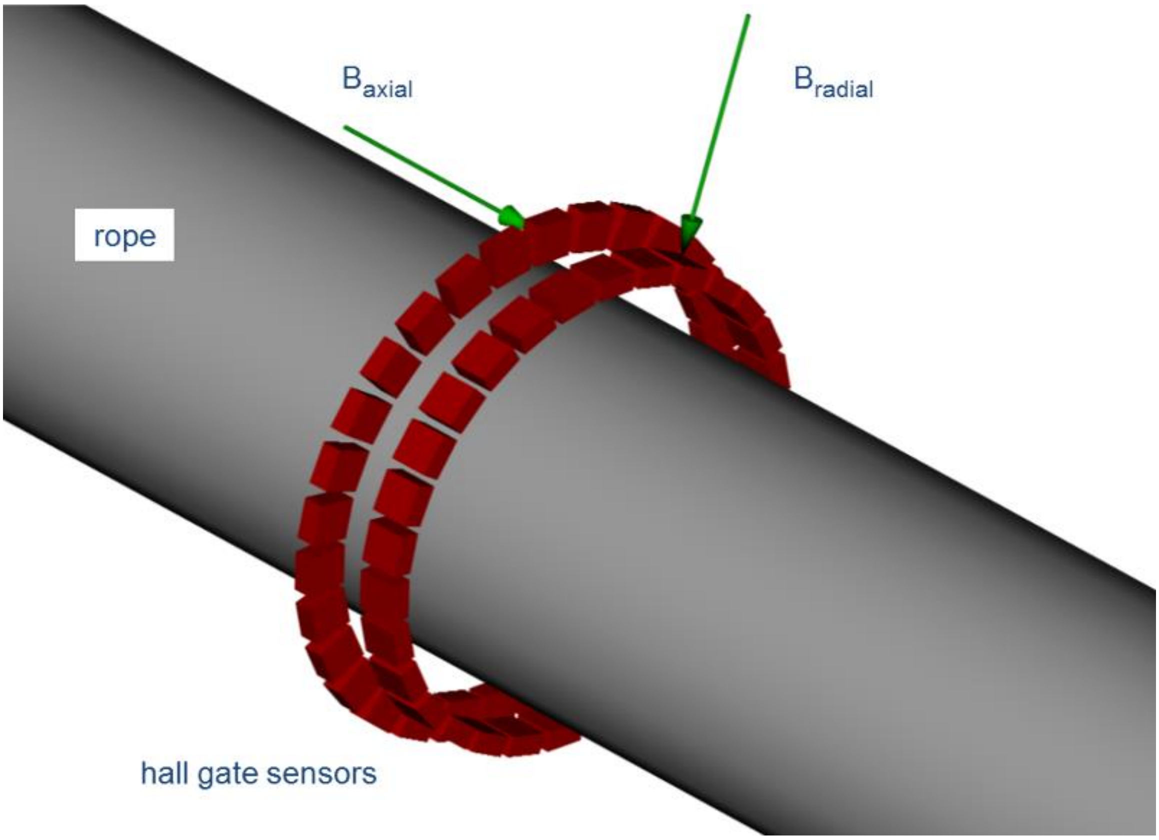


Figure *16*: Sensor arrangement for a high-resolution testing system.

Although FEM-calculations gave good results for single wire breaks (see Figure *17* and Figure *18*), it was found that the linear current density method can map the effects of a cluster of wire breaks with higher accuracy.

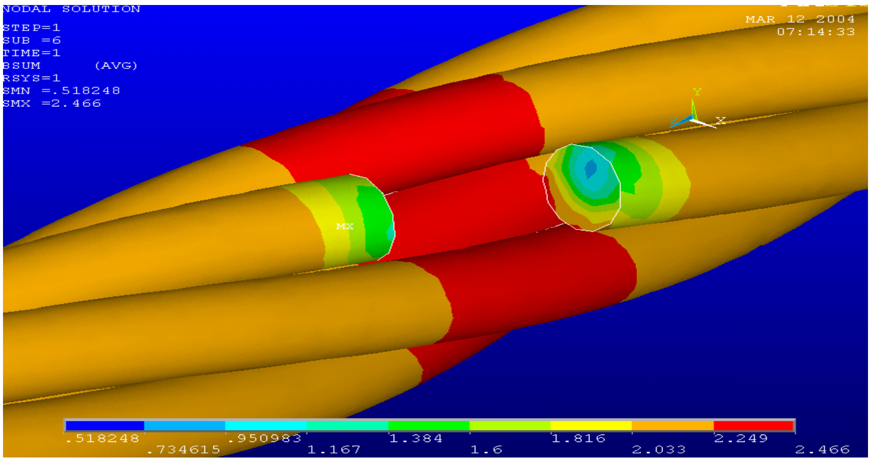


Figure *17*: Simulated leakage field of a wire break computed with finite-element modelling.

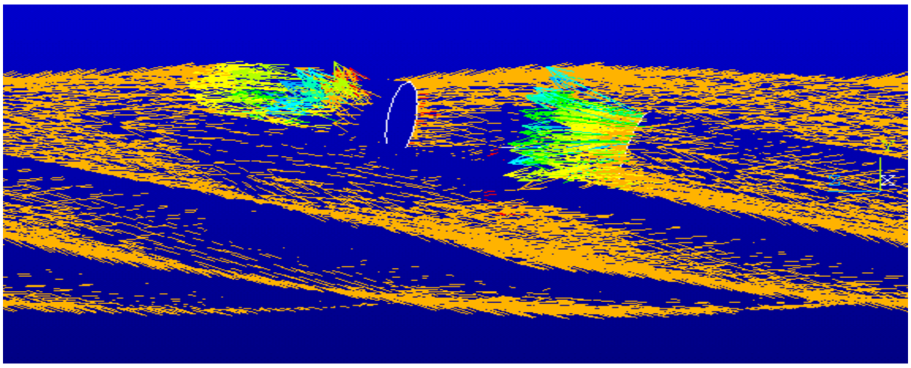


Figure *18*: FEM vector-field of a wire break.

Using the mathematical expressions (3) and (4) derived from linear current density theory, a 3D envelope of the leakage field can be constructed (see Figure *19* and Figure *20*) and corresponding legend in Table 3.

$$B_{axial}(z_n) = \frac{I}{4\pi} \cdot \frac{\pi \cdot d^2}{4} \cdot \sum_k \Delta B(z_k) \cdot \frac{2(z_k - z_n)^2 - (a)^2}{\left((z_k - z_n)^2 + (a)^2\right)^{5/2}} \quad (3)$$

$$B_{radial}(z_n) = \cos\alpha \cdot \frac{I}{4\pi} \cdot \frac{\pi \cdot d^2}{4} \cdot \sum_k \Delta B(z_k) \cdot \frac{3 \cdot (z_k - z_n) \cdot a}{\left((z_k - z_n)^2 + (a)^2\right)^{5/2}} \quad (4)$$

$B_{axial,\ radial}$	mT	axial / radial components of magnetic flux density of the defect field
z_n, z_k	mm	longitudinal coordinate in relation to wire break end
I	A	current
d	mm	wire diameter
ΔB	T	difference in flux density
a	mm	distance from measuring point on surface to rope axis
α	degree	angle

Table 3: Nomenclature used in the Nussbaum formulae [7].

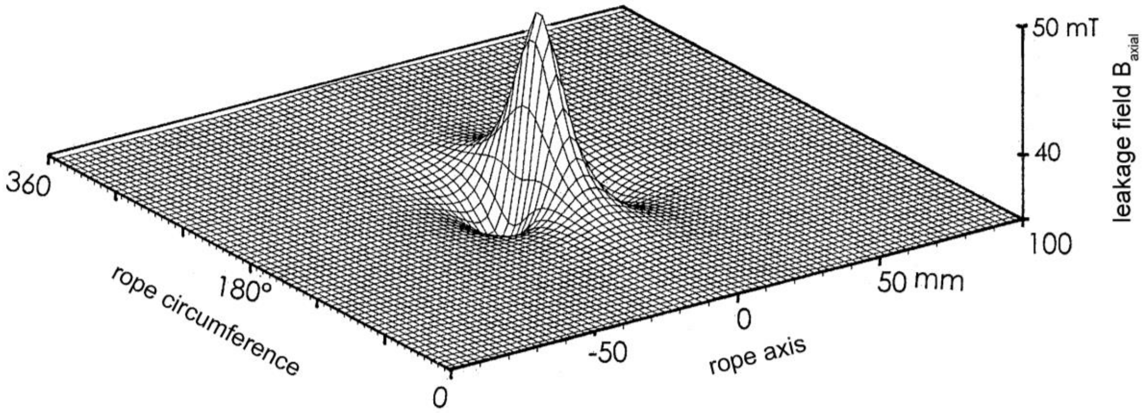


Figure *19*: Theoretical leakage field for a single wire break.

The same method can be used to model the 3D leakage field measurements for a combination of defects using the Hall sensor heads (see Figure *16*). By giving the inspector tools to tune the visual display of the image and to adjust the colour-scale from what is alarming to what is harmless, the interpretation of the presentation of resulting signals can be far more detailed than is possible with conventional 2D coil signals.

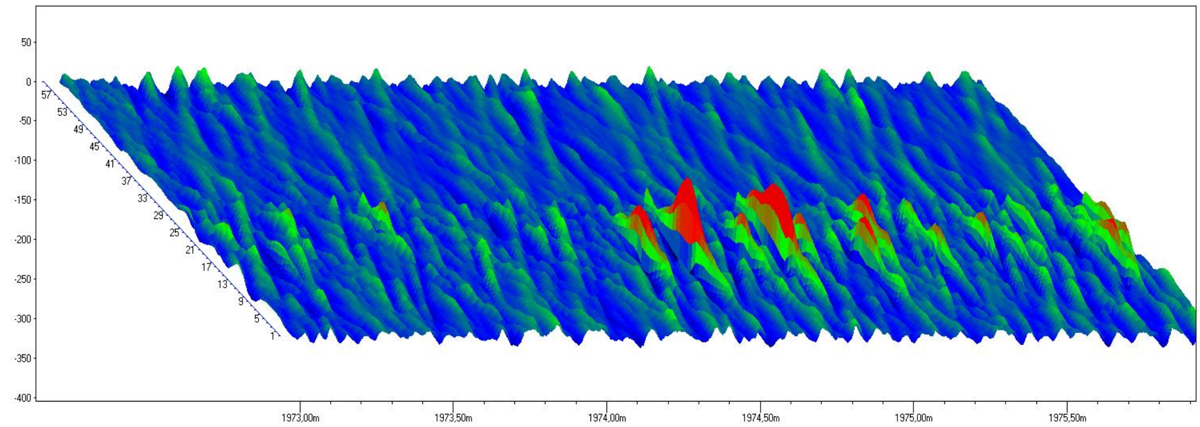


Figure *20*: 3D display of wire-break signals measured with the high-resolution device.

Using these methods, it is possible to access more information about a defect from the shape of the magnetic field:

- the location around the rope circumference (e.g. upper or lower side of a track rope),
- the shape of the defect,
- the arrangement of clusters of wire breaks,
- the depth within the rope,
- (for stranded ropes) the distribution of wire breaks, e.g. in a single strand.

High-resolution inspection is used mostly for damaged former saddle areas of shifted track ropes. The test generates data which can help to evaluate the damage and to identify the damaging mechanism.

2.5 Device calibration

Calibration should demonstrate that a particular MRT device is capable of detecting a defined, small, wire defect within the maximum metallic cross section of a rope for which the device is designed. An example of a possible calibration procedure is given in standard EN 12927-8. A correctly calibrated device guarantees the state-of-the-art quality of a magnetic rope test. The inspector should, nevertheless, be aware that there are various types of damage that no MRT device is capable of detecting (see Limitations in section 5.5).

2.6 Distance measurement

In order to correctly correlate a MRT signal with the relevant location along the rope which has been tested, an accurate distance measurement is necessary. This is usually provided by means of a measuring wheel (see Figure *21*) which is fixed to the test head and which is driven by the rope being tested or by a carriage wheel of the cabin while inspecting a track rope. A pulse generator is attached to the measuring wheel providing increments of movement from which to locate the signal.

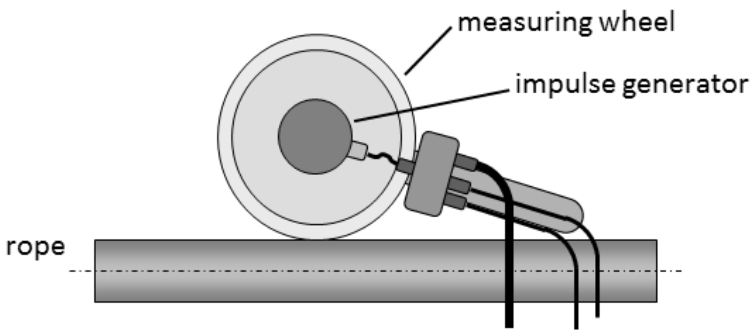


Figure *21*: Measuring wheel installed on the rope.

3 Experimental set-up

***Summary**: MRT tests may be performed either on a fixed rope by using an MRT device which moves along the rope span, or with a fixed MRT device through which the rope moves. A remote data system connected by shielded wire or by wifi, is used to record the signals from the MRT device for analysis. The details of the installation and the testing conditions both have a significant influence on the reliability of the MRT method and are discussed in this Section. Other important features relating to the safety of the rope, the ropeway, MRT equipment and personnel are also considered here.*

3.1 Prerequisites

3.1.1 General considerations

Prior to making an MRT test, it is important that the inspector knows the rope environment such as the identification of the rope, and the ropeway on which it is installed. Next it is necessary to establish the functional role of the rope which has to be tested:

- track,
- tensioning,
- hauling,
- hauling-carrying.

The answer will determine whether the rope is fixed or moving and the installation procedure will differ accordingly.

With fixed ropes, such as tension ropes, track ropes on roller chains, etc., the rope must be removed, shifted or loaded to facilitate the MRT inspection correctly. When any abnormal shape or amplitude of the signal is detected during MRT test operation, the inspector must perform a visual inspection or an investigation by any other suitable method. Available documentation on the rope history, including related signatures especially those of former test providers, must be considered to understand the likely future progression of rope degradation in the context of this history interpreted from damage identified by the inspection.

Choose the MRT device set-up using suitable parameters !

3.1.2 Test preparation

The details required by the inspector when preparing for an MRT test include in particular:

- the nominal rope diameter and the maximum diameter at splice knots, if applicable, to make the right choice of test head, coil diameter and sliding guide,
- the rope construction, its cross-section area and the percentage of metallic area for the different wires in the construction, which is important to establish the accuracy which can be achieved in the test,
- the ropeway profile and the position of tower saddle ends, small breakover diameters, slack carrier clamp locations, and reverse bending locations, all of which are important in making the right choice for MRT installation and in ensuring safe operating conditions,
- the expected length of rope being tested and the number of splices if applicable,
- the weather conditions during MRT tests are also important both as regards safety and the value of the data obtained.

3.1.3 Operating procedure

An MRT inspection procedure must be clearly defined so that where there are multiple inspections of different sections of the same rope, these sections overlap. Where there are MRT inspections on different sections of a rope, such as the free length, roller-chain section, and counterweight sections, it is advisable to maintain a detailed inspection plan for the different sections, including a time schedule, to avoid missing critical parts of the rope.

The MRT device should meet all the requirements listed here:

- to ensure correct magnetisation the rope diameter must be in the stated range of the test head ,
- to minimize air gap effects the dimension of the coils must be chosen to accommodate the rope diameter at splice knots. But note that rope should be centred within coils to preserve an axial symmetry of measuring.

Choice and purpose of test markers

Ferro-magnetic steel wires taped on the surface can serve as test markers:

- to check that the MRT device is functioning,
- to indicate the start/stop position of the test,
- to calibrate the MRT signal amplitude in relation to the diameter of detectable wires,
- to check the signal polarity.

Figure *22*: Set-up of MRT device on a fixed rope (left), and moving rope (right).

3.2 MRT device set-up

3.2.1 Set-up on fixed rope

The MRT device must be attached to a carriage with a rigid link and pulled along the rope span as shown in Figure *22* (left). It is necessary to ensure that there is adequate clearance around MRT device throughout the whole rope length, and the inspector must make a careful note of the position of towers, saddles and slack carriers.

Throughout an inspection, communication must be maintained between the MRT inspector and the ropeway driver in order to control test speed and to be able to stop when necessary. Adequate portable devices may be needed to power the data acquisition systems. Extra rollers may be used to reduce the friction on the MRT device instead of using sliding guides. It is necessary to make sure that the cable link is working for different inclinations of the carriage along the rope. Note also that the carrier, including the test device, the link equipment and any additional platform may not fit in the opposite station.

Reduce speed near tower saddles!
When testing track ropes, the speed is usually reduced and the test head opened when approaching sections of the rope on tower saddles.
When coming closer to a tower and slowing down, it is necessary to maintain a safe distance. For this reason a section of rope might not be tested so it is important to check that the shifted rope section is tested thoroughly. It is recommended that when testing the relocated rope the MRT test is in the same direction.

3.2.2 Set-up on moving rope

- Choose a suitable place along the ropeway loop to install the MRT device as shown in Figure *22* (right).
- Choose a test speed for the rope similar to that used in previous tests. Note that if, when running the test, vibration affects the quality of the MRT signal, decreasing the rope speed may introduce problems with comparison to previous results. An alternative is to choose another suitable position for the MRT device.
- MRT devices must be attached by means of elastic links to fixed points, if possible constraining both directions of motion. This should prevent the test equipment from being damaged during rope movement and to smooth vibrations caused by the uneven surface of a stranded rope.
- Prevent twisting of the MRT device around the rope by using a counterweight, for example.
- Particular care is required for splice elements or incoming vehicles.

Special rope sections, such as a splice section, require additional inspection which is not discussed further here. In the case of hauling ropes, it will be necessary to perform two MRT tests with the device in different positions, as shown in Figure *23*, to cover the full length of the rope between terminations.

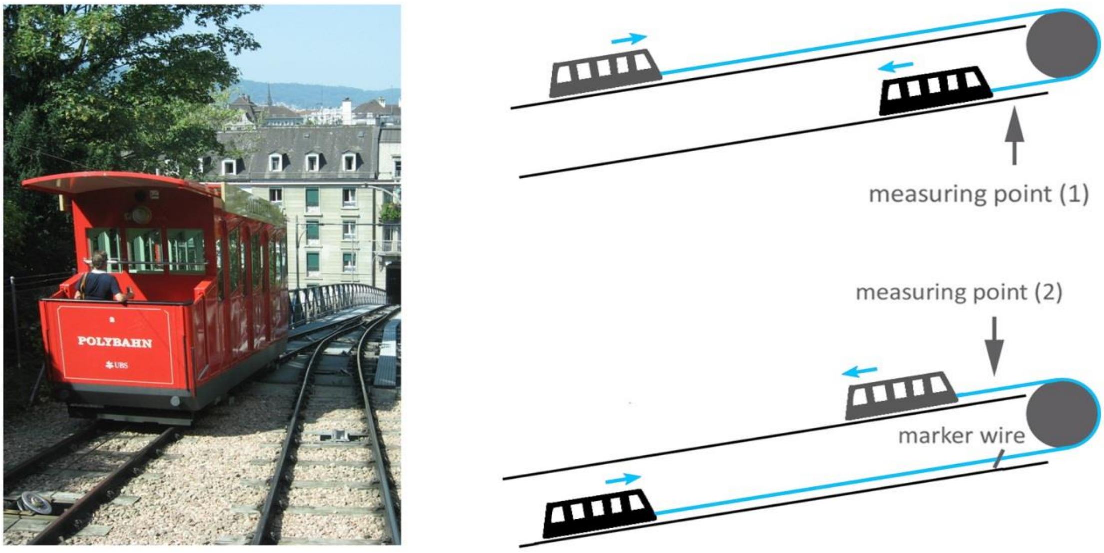


Figure *23*: Measurement of hauling ropes in two steps.

3.3 Caution for specific rope sections or special ropes

This booklet does not consider the specific inspection demands for special ropes or sections of ropes such as tension ropes, rescue ropes, signal ropes, and stays, at tower saddles, saddles, roller chains, and at terminations.

4 Magnetic leakage signal processing and wire break analysis

***Summary**: Some important features related to sensor conditioning and data acquisition are explained to ensure an optimal quality of measured magnetic signals during MRT tests. Signal processing techniques are then introduced to explain how to distinguish wire break signatures from the rope ground signal. General guidelines for wire break analysis are given and the main issues are illustrated by several case studies. Finally, with a view to overcoming the limitations of currently available MRT technology for identifying internal damage, recommendations are discussed for advanced techniques.*

4.1 Main purpose and prerequisites

Prerequisites to ensure high quality measurements are:

1. High quality design of MRT devices with
- sufficient magnetic saturation of the rope to ensure that inner wire breaks can be detected,

- special designs to avoid the propagation of axial vibrations in the testing instrument.

2. Optimal MRT operation on a rope requires:

- an adequate choice of measurement coil diameter and width in relation to rope diameter,
- a smooth motion and a velocity of the rope relative to the MRT device which is high enough (v > 0.2 m/s). For manual operation, rollers need to be used which provide adequate smoothing of the movement of the MRT device relative to the rope, otherwise the signal quality will fall
- a state-of-the-art data acquisition system, which can be either computer, or paper, based. The acquisition system should be capable of registering the full frequency bandwidth of the wire rope testing instrument, for example, wave-numbers (spatial frequencies) up to approximately 250 m^{-1} for a "4 mm" coil width. Note: this value must be multiplied by the expected instrument velocity to calculate the upper frequency limit in Hertz.

4.2 Instrumentation and data acquisition

The first relevant question in designing an MRT device concerns the decision as to which signals should be recorded to provide evidence of wire breaks. Classical LF type MRT devices can deliver the following information:

1. analogue signals for each LF coil of the instrument,
2. position and speed of the rope relative to the instrument, which may be as either an analogue or a digital output,
3. current direction of motion,
4. additional signals depending on the capabilities of the MRT device and the recorder.

From a signal processing point of view, the first three signals listed above are necessary for an optimal analysis. A compromise is nevertheless necessary to balance a lossless quality of wire rope signal with the resulting quantity of data which must be recorded.

Three different methods of data acquisition are commonly used with currently available equipment:

1. time-based analogue acquisition comparable to paper recording,
2. time-driven digital acquisition,
3. space-driven digital acquisition.

Analogue paper acquisition is outdated and its operation is only continued for historical reasons and hardware compatibility purposes.

Analog vs digital

- Advantages: state-of-the art recorders that can display the coil signal over the full bandwidth of the testing instrument without distortion, can provide good quality MRT tests. By comparison with digital acquisition devices, paper-based recordings provide a better overview of the test signal.

- Disadvantages: when using a paper based acquisition device for complex signals, it may be necessary to repeat the recording many times with different settings to obtain a good analysis. Only experienced MRT operators may be familiar with such procedures.

The comparison of the advantages and disadvantages of time-based as compared to distance-based acquisition is not obvious. Although time-based data acquisition may appear much more straightforward at first sight, distance-based acquisition is more meaningful from the physical point of view because most key features of wire rope signals are position invariant and not time invariant.

Time vs distance

- Advantages: with reference to the Nyquist-Shannon sampling theorem as applied to signal analysis, time-based acquisition seems to have a significant advantage over distance-based acquisition because all the relevant dynamic information is embedded in time-based signals. When the sampling frequency is known, anti-aliasing filters can be used to remove successfully any undesirable acquisition artifacts.

- Disadvantages: again, because wire rope testing data are position invariant and not time invariant, recorded time-based data must be transformed into the distance domain for analysis. As the relative rope speed is not usually constant during an MRT test, the recorded time-based data will not be equally spaced. Resampling data by using interpolation techniques can be used but lossless signal pre-processing with an anti-aliasing filter is no longer acceptable because the dynamic components of the signal are lost. Note: little difference between time and distance based recording is evident when MRT tests are performed at constant speed!

4.3 Signal conditioning

MRT signals need to be conditioned before being sampled with an analogue-to-digital converter to achieve high quality recordings.

Key issues in signal conditioning

Because of high impedance, signals from LF-coils are sensitive to cable length and contact problems. To overcome such problems and prevent any resulting distortion, a signal amplifier directly linked to the testing device may be used. Another solution is to sample the signal within the testing device. An anti-aliasing filter should always be used before the sampling to avoid problems during signal interpretation and digital signal processing. Anti-aliasing filters should be configured to satisfy the Nyquist sampling theorem. Crosstalk, resulting from long cables between testing instrument and the data acquisition system, is generally not a problem but should be considered and minimized by the choice of appropriate shielded cables. Crosstalk disturbance can result, for example, where there is a speed-dependent offset of the test signal.

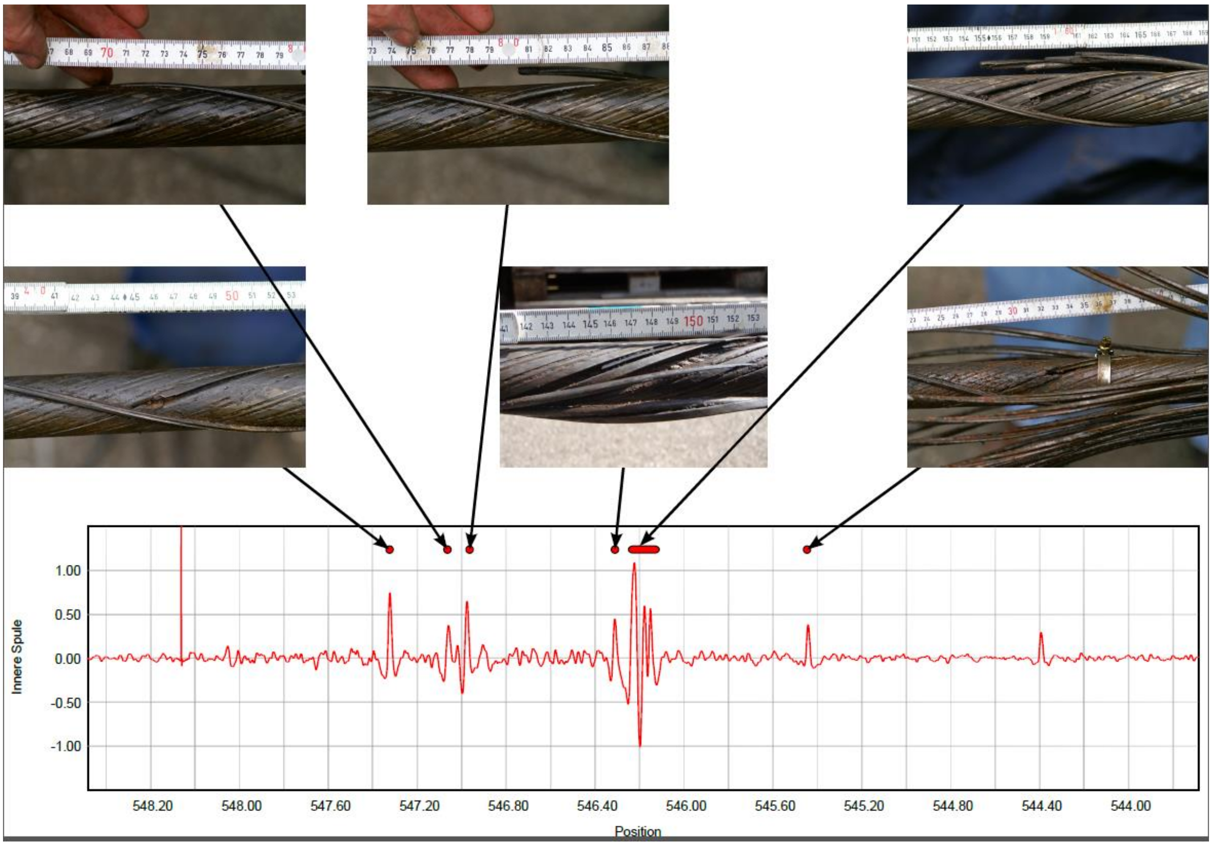


Figure *24*: MRT signal and associated wire breaks in a track rope (second layer).

4.4 Signal processing and wire break analysis

MRT wire break signals are not just clean single peaks rising above some rope ground signal. Practical MRT signals are a combination of the following signal components as seen in Figure *24*:

- the rope signature or ground signal: the signal component resulting from the geometrical design of rope (strand lay length, wire gap variation, etc.),
- "useful signal": the signal component linked to rope defects of all kinds (wire breaks, wear, nicks, loss of metallic area),
- disturbances of any kind: for example the effects of eddy currents, unsteady motion, electro-magnetic disturbances , etc.

It is important to be aware that a MRT signal derives from the superposition of signal components caused by a variety of physical effects.

Various rope anomalies with similar MRT signatures!

The acquisition of the test signal during MRT testing corresponds to a mathematical transformation that maps the actual rope geometry onto a test signal. When a design of MRT device and the direction rope of operation are chosen, genuine defects within the rope create unique MRT defect signatures (surjective mapping). But, this mapping is not injective and the actual defect in a rope can not be recovered from the testing signal unambiguously. Thus, the mapping procedure from the physical wire rope with defects to the testing signal with defect indications is "lossy". This means that some information gets lost during the testing process and cannot be recovered by any interpretation or mathematical method. As a consequence, the interpretation of wire rope testing signals is never unambiguous - there are only fault configurations that are more probable than others.

In practice, wire break analysis is similar to a "pattern-matching" procedure. Once, through experience, a collection of wire break signatures has been explicitly correlated with specific sets of defects, MRT operators will try to recognise these known patterns in the test signal. This pattern-matching procedure can be performed either by hand, when using the intuition of an experienced inspector, or by means of mathematical procedures.

Before any fault analysis begins, the signal from a wire rope test should be standardized. Offset and the effects of speed variations must be removed as far as possible. Figure *25* shows a collection of calculated signal patterns for wire breaks in a track rope. Depending on the cross-section of the broken wire, the distance between the fracture faces and the position in the rope cross-section, the size and the shape of the pattern will vary considerably.

The non-injective***** mapping process further influences the analysis process. A standard indication-pattern (search pattern) must be defined and then must be searched for in the test signal. It is only possible to search for defects that can be standardized and associated with an indication-pattern, and their mapping onto test signals must produce a significant indication within those signals.

***** “non-injective” is a mathematical term indicating in this context that several different rope defects can generate similar MRT signatures.

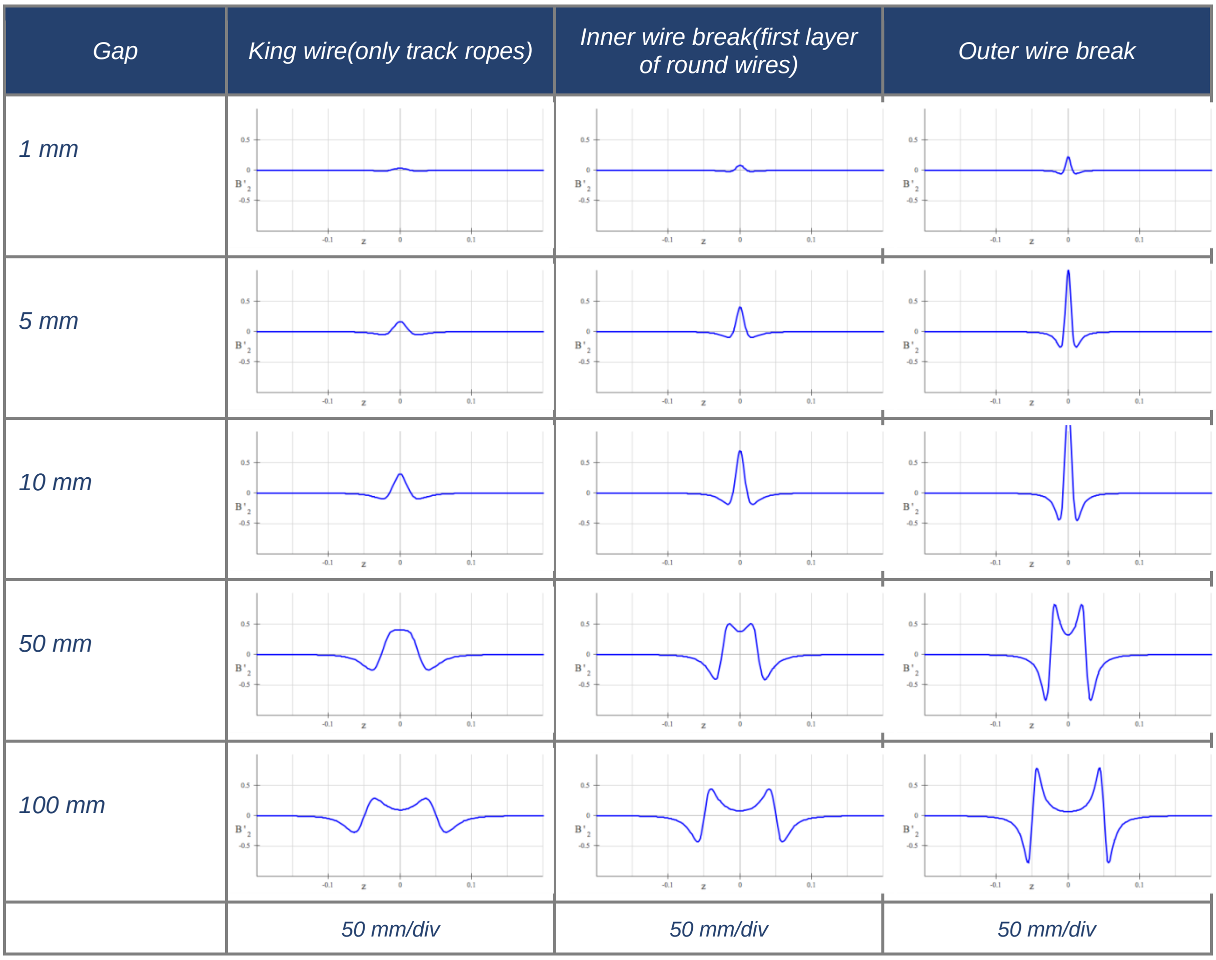


Figure *25*: Different search patterns as a function of the distance between the fracture faces of a wire (gap) and the position of the wire within the rope.

The patterns have been calculated for a 40 mm wire rope with a break in a 3 mm wire. The horizontal axis corresponds to the rope length, the vertical axis corresponds to the amplified voltage of the LF-coils. The patterns have been calculated using the dipole method.

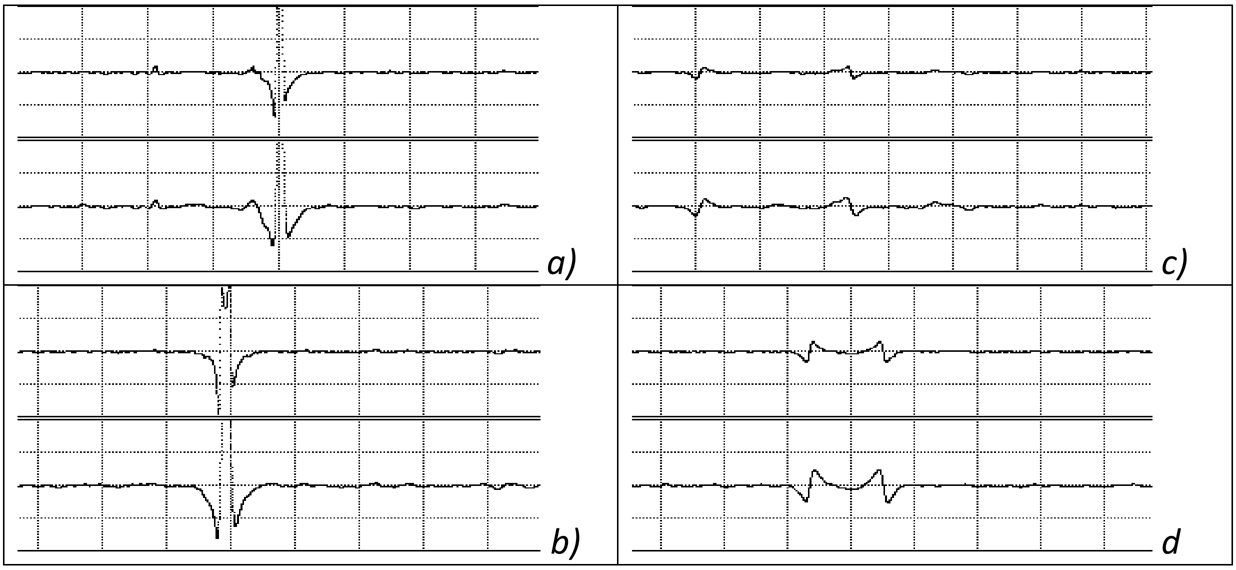


Figure *26*: Actual MRT signals for defects in a 68mm track rope: a) and b) two indications of a broken Z-wire with different gaps; c) and d) two different indications of a missing inner wire.

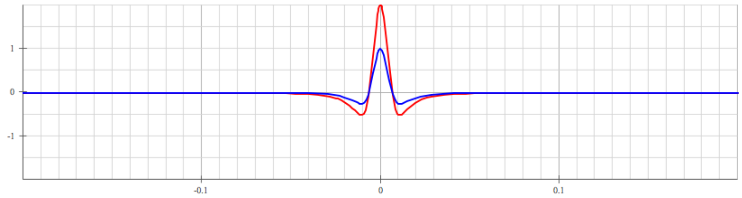
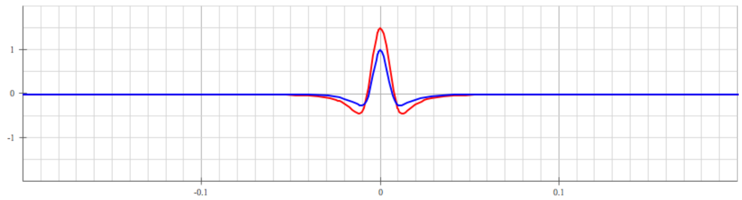
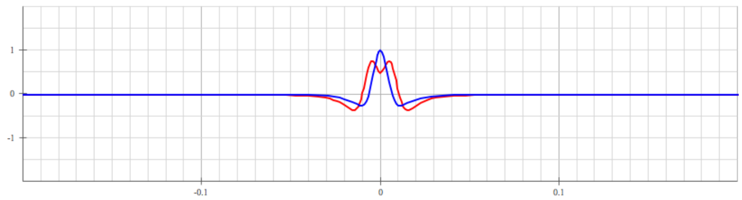
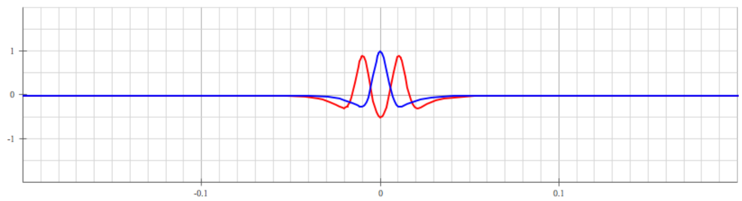
Comment	Diagram
2 wire breaks at the same position	
2 wire breaks with a distance of 5 mm	
2 wire breaks with a distance of 10 mm	
2 wire breaks with a distance of 20 mm	
	10 mm/div

Figure *27*: Calculated signal for typical wire rope testing equipment: a) blue: single wire break, b) red: two wire breaks.

4.5 Limitations of MRT technology and the main issues

The limitations of MRT technology are related to the following:

1. **Changes of magnetic reluctance during rope service life**: Several physical effects have an impact upon the MRT signal content, for example the variation of the rope cross-section (expected), but also unwanted effects like eddy currents in the rope. Such effects cannot be identified or differentiated in either time-based or in distance-based recordings.
2. **Limited resolution of testing instruments**: The coil geometry restricts the sensitivity of a testing instrument to a well-defined range of wavelengths. Faults outside this range can barely be detected, for example corrosion pits (wavelength too short,) or almost uniform wear - (wavelength too long).
3. **Rope ground signal**: The relative amplitude of defect signals to the rope signature signal affects the signal-to-noise ratio (SNR). Signals with a too low a SNR cannot be analysed reliably. The SNR must be taken into account in any wire break analysis.

Note: ropes with a SNR that is too low to allow reliable interpretation should be discarded.

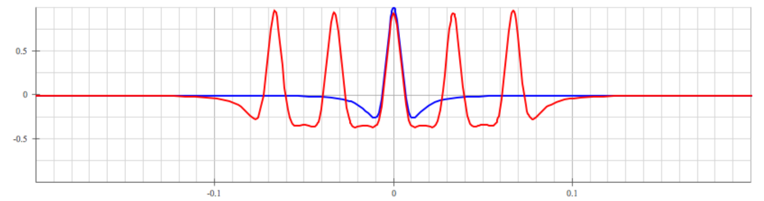
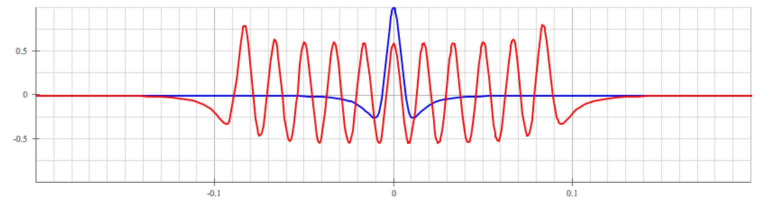
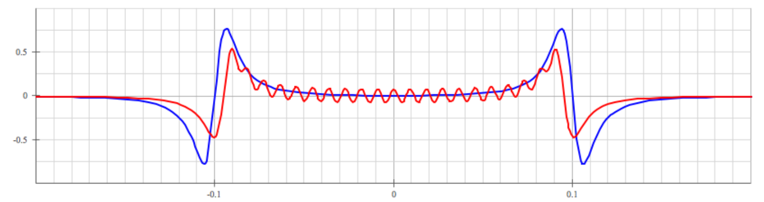
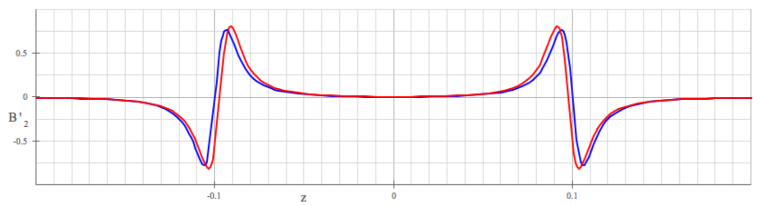
Comment	*Diagram*
5 wire breaks within 0.2 m	
11 wire breaks within 0.2 m	
21 wire breaks within 0.2 m	
41 wire breaks within 0.2 m	
	10 mm/div

Figure *28*: Theoretical model of the effect of the restricted resolution of a typical wire rope testing instrument for both single and multiple wire breaks: blue lines: single wire break, red lines: multiple wire breaks.

In order to avoid problems related to the limited resolution of MRT devices, all documents of previous tests including signal plots should be consulted when performing the wire-break analysis. This is the only way to assess the evolution of damage: previous plots may also contain hints indicating whether degradation could have reached the limit or not. But it is important to be aware that inspectors' reports are generally not sufficiently detailed to eliminate misinterpretations.
An example relates to internal corrosion in track ropes, for which it has become apparent that MRT analysis can sometimes over-estimate the loss of metallic area. It is therefore strongly recommended in such cases that complementary tests, such as radiography, should be performed to avoid such misinterpretations.

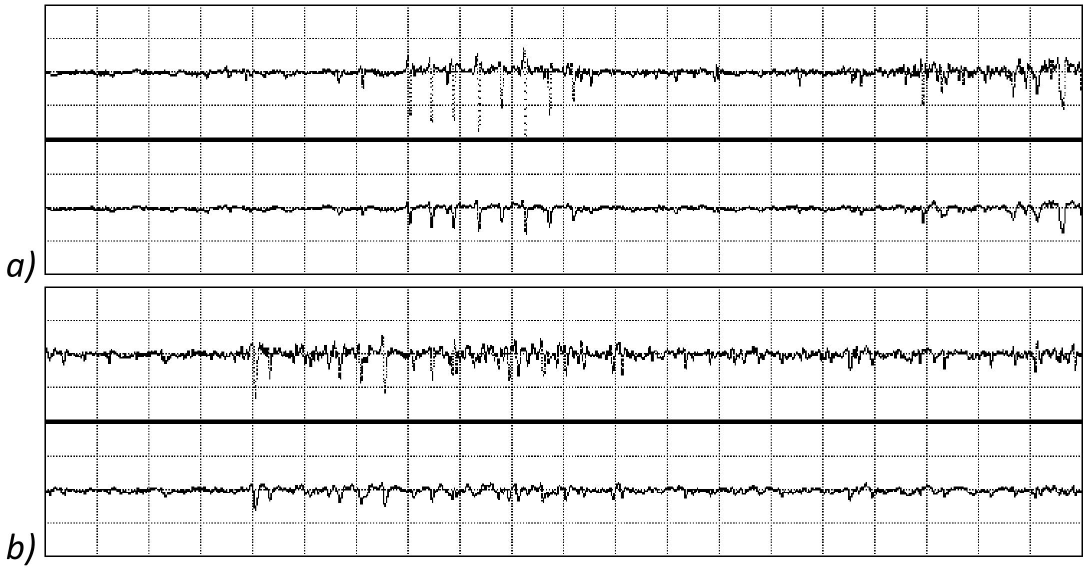


Figure *29*: Two successive samples of MRT signal indicating corrosion in a 50mm diameter, 12 year old, track rope resting on the drum. The rope was dismantled and neither wire breaks nor a significant loss of metallic area due to corrosion were found.

There are numerous issues still open, some of which are unanswerable, that need to be addressed by the scientific rope community. A selection of such questions would include:

1. Why does the ground signal of spiral strand or locked coil ropes apparently contain combinations of components with specific frequencies while simple magnetic theory forecasts a flat line?
2. What is the influence of eddy currents in testing track ropes, especially in the presence of internal stress corrosion cracking (role of electrolytes)?
3. Most MRT operators have experienced being faced with MRT signals indicating a series of defects that led them to discard the rope: but after opening the rope no wire breaks were found. Why? The sensitivity of MRT devices to impedance changes may be a clue to give a suitable explanation.

Extensive experience of scientists like in references [6] and [9] may be relevant to rightly answer these questions. Following section is for advanced readers interested in new approaches to improve signal interpretation.

4.6 Advanced signal processing

4.6.1 Artificial Neural Networks (ANN)

One key problem in any numerical search for wire breaks is directly related to the amplitude of the indications: when considering wire-breaks with small gaps, the amplitude of the resulting indications are directly proportional to the width of the gaps. For safety reasons wire break patterns of any amplitude must be taken into account in an analysis to detect wire breaks in an early stage, when the gap width tends to be small. The trigger level of the pattern matching method, therefore, needs to be chosen slightly above, but as close as possible to the level of rope ground signal. The immediate drawback of a low trigger level is the risk of false trigger events: large indications of wire breaks may be marked at least twice, or trigger events will occur at positions where there is any disturbance, or elevated noise.

There are two possible ways in which to overcome this problem: manual correction, or the application of advanced and specialized decision making or error-correction algorithms.

Several strategies may be suitable for the design of error-correction algorithms: one is to use artificial neural networks (ANN) [10]. The advantage of artificial neural networks is their flexibility: they are capable of managing complicated signals, even with more than one component (different coils, speed signals, etc.), and they are "intelligent" in the sense that an expert can define training samples from which the network "learns" to give the correct answers.

Artificial neural networks have been successfully applied to error correction after pattern matching and to categorize indications. The example shown in Figure *30* illustrates the classification process in a rather complex situation.

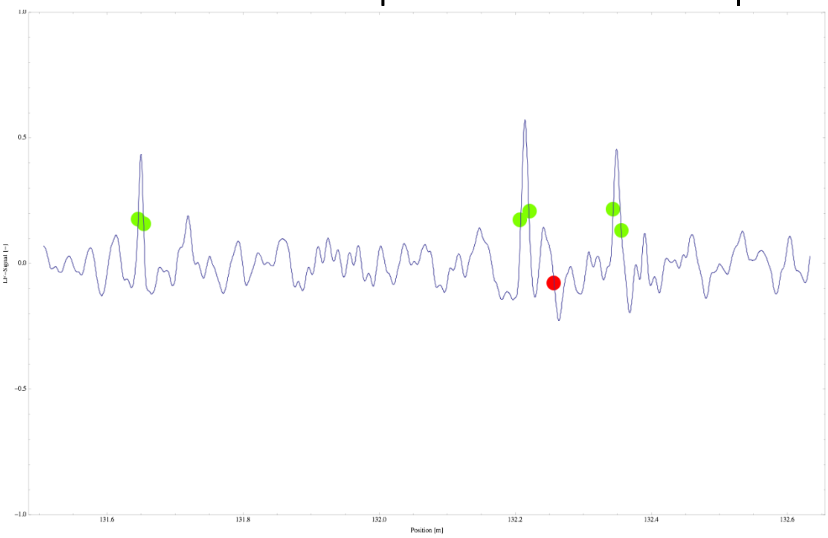


Figure *30*: Classification of wire breaks after pattern matching. Trigger points of the pattern-matching step are marked with solid dots. Green dots are recognized as wire ends, the red dot is marked as a false trigger event.

The artificial neural network infrastructure allows experts to build up a knowledge base and to share their knowledge. On the other hand defining training samples and optimizing a complex net is an extremely time consuming procedure. Neural nets are usually trained “on the job” by an expert. A detailed knowledge of the underlying system is necessary to train a neural net. Inappropriate training leads directly to unusable nets.

4.6.2 *Wavelet Scalogram*

Identifying key features or defects from an MRT signal is commonly performed by hand in the space domain by inspectors. A wide range of other tools from filtering theory and Fourier analysis [9] may be applied as a complementary tool. Wire break signatures cannot be separated from the rope ground signal by means of standard filtering because the related frequency spectra overlap one another. An alternative is to use a variation of a tool called a Wavelet Scalogram that makes it possible to extract the instantaneous spectrum of a MRT signal and thus follow the ascending wavenumber (spatial frequency) with respect to the position of the device.
Blindness of overlapping signals, or complex signals, encountered by MRT inspectors may partly be overcome by using sophisticated signal processing tools such as the wavelet scalogram.

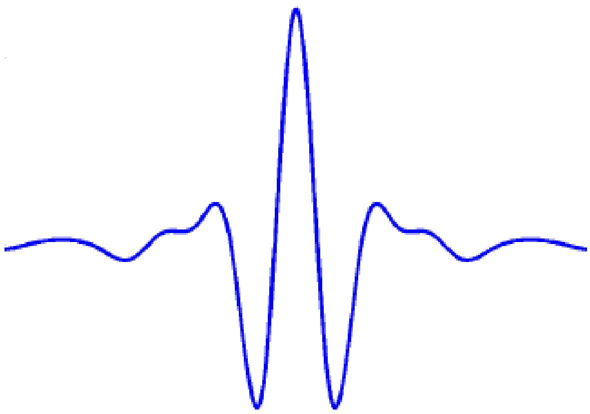


Figure *31*: A *spline wavelet* which is very similar to a wire break signature !

Wavelets are universal mathematical *approximators* structured to span a signal in terms of a superposition of elementary signals similar to little waves (see Figure *31*), thereby making possible the analysis of its principal components.

$$W_\psi^s(a,\, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} s(t) \overline{\psi\left(\frac{t-b}{a}\right)} \, \mathrm{d}t$$

The wavelet transform above makes it possible to span an MRT signal in both space and frequency domains rather like a mathematical microscope. It makes it possible to stretch the main components along the space axis while inspecting the local spectrum content at the same time. An optical analogy is employed hereafter.

Optical analogy: mathematical microscope

$$\mathbf{b} \longleftrightarrow \text{Focus}$$

$$\left(\mathbf{a}\,\Delta\mathbf{t}_{\psi}\right)^{-1} \longleftrightarrow \text{Magnification factor}$$

$$\psi \longleftrightarrow \text{Optical lens}$$

In other words, it is possible to characterize a wire break signature by following its space signature along the rope and at the same time by following wavenumbers contained in the wire break signal.

On a two dimensional map called a scalogram, several potato-shaped coloured clusters emerge from the white background. A wire break signature may, for example, be related to a peak-shaped cluster that yields relevant information upon the kind of defect and its geometrical properties.

The wavelet scalogram is a useful tool that makes it possible to separate wire-break events more successfully from the rope ground signal, or to improve the understanding of complex MRT signals with, for instance, ill-separated overlapping signatures, or to measure the opening of a rope defect.

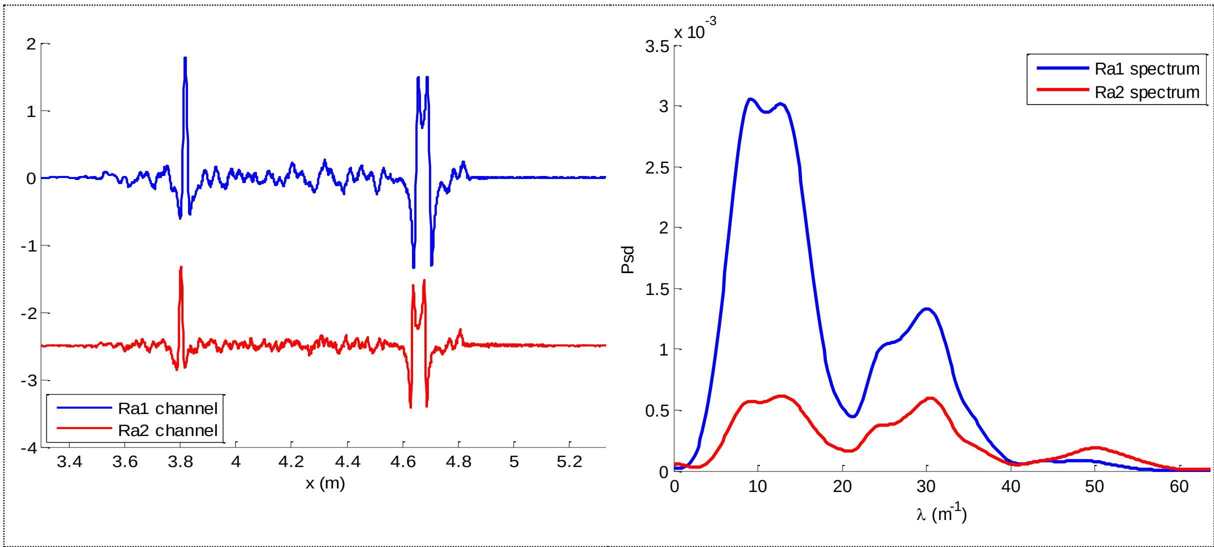


Figure *32*: An MRT analysis of the Hoffmann[1] rope: a) Ra1 and Ra2 coil signals, b) power spectra.

[1] *rope belonging to the IFT rope library, University of Stuttgart.*

For example, MRT signals measured on the Hoffmann[1] sample rope by using an SMTR 40 device make it possible to differentiate two reference defects: a single narrow wire break followed by either a single wire break with an extended gap or a sequence of two neighbouring wire breaks as shown in Figure *32*.

The power spectrum plot highlights two peaks centred around wavenumbers $\lambda_1 = 12\ m^{-1}$ and $\lambda_2 = 30\ m^{-1}$ yielding potential information on the wire breaks. This spectral information nevertheless remains difficult to analyse since it is impossible to state whether one peak characterizes the first or second wire break, or both.

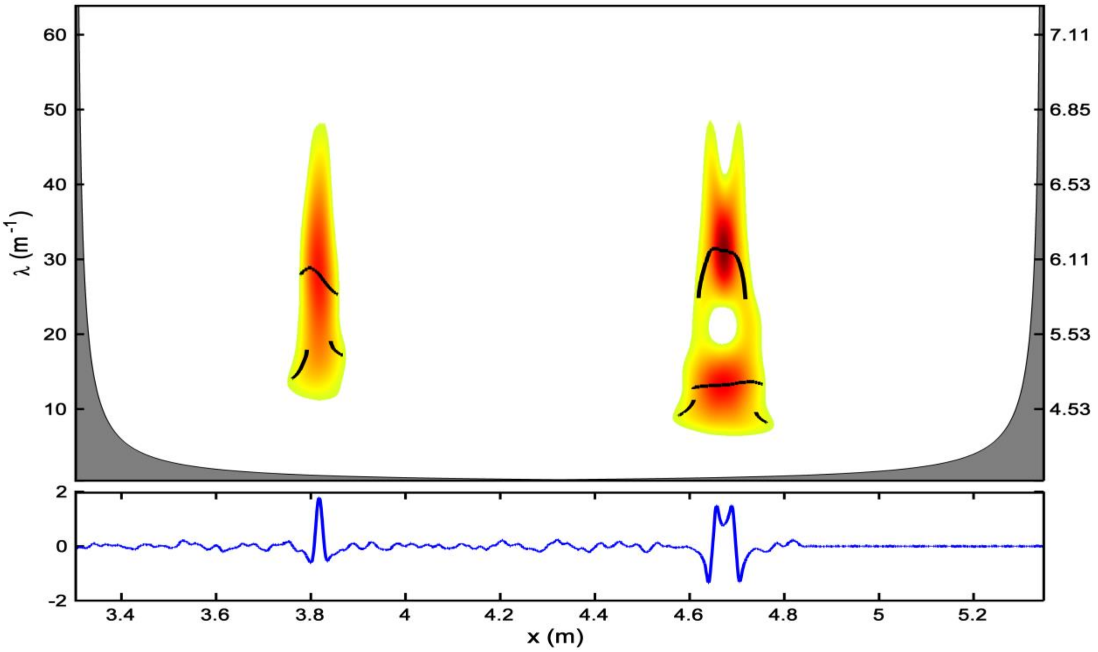


Figure *33*: The wavelet scalogram of the Hoffman rope wire-break signals.

The wavelet scalogram shown in Figure *33* makes it possible to follow the spectral content of the wire breaks along the rope length. The first defect with a spectrum ranging from (low) $\lambda = 12\ m^{-1}$ to (high) $\lambda = 50\ m^{-1}$ wavenumbers typically represents a single wire break, whereas the second defect appears to be divided into two sub-clusters.
Considering that only clusters starting from low and going to high wave lengths can be related to a wire break defect, a wavelet scalogram makes it possible to separate artefacts from wire-break signatures and to recognize the scenario of a single wire break with extended gap. A closer examination of the ridge curve of the right hand cluster makes it possible to estimate the wire-break gap by measuring the distance between the upwards and downwards steps.

5 Rope discard criteria

***Summary**: The identification of wire-breaks or any other damage within a rope is routinely performed to assess the loss of metallic area and consequently the* *residual tensile strength of the rope. The philosophy of discard criteria which take account of loss of metallic area over various reference lengths - short, medium, long - is explained, and the related failure mechanisms of rope are introduced.*

5.1 General

Discard criteria always relate to rope stress, the chosen safety factors, the number of bending cycles, maintenance, environmental conditions, etc. Discard criteria should not be exceeded between two consecutive visual and / or MRT inspections.

When determining the limit of operating life, all available information and assessments should be considered, including:

- an estimation of operating time (fatigue cycles),
- the results of the magneto-inductive test (MRT),
- the results of the visual inspection,
- geometrical measurements,
- the results of any other optional test methods which can provide a general overview and assist in making the recommendation to discard or retain the rope in service.

A rope is invariably a safety-critical component and in order to ensure that it is suitable for continued use, limits to its degradation (discard criteria) must be defined.

These limits should ensure that:

- there is no excessive reduction of the breaking force,
- there are no excessive structural changes to the rope, potentially leading to secondary problems (e.g. derailment, incorrect clamping, etc.)

The possible causes of a decrease of the tensile strength of a rope (including end connections or splices), are:

- reduction of the metallic cross-section (wire breaks, inner and outer wear, loose wires, corrosion),
  Note: loose wires / loose strands should be considered as broken,
- deterioration of the end fixing due to wire breaks, or corrosion in the area of the end fixing or at the entry to a socket, as well as unacceptable draw,
- failure of a splice based on sliding tuck tails, accumulation of wire breaks in tucks, or a significant reduction of diameter at the tuck tail ends, etc.,

- reduction of strength due to heat (caused by lightning, fire, electrical discharge), or strength reduction from a notch effect, or steel embrittlement,
- a significant change in lay length can cause increased stress in some wire layers relative to others.

5.2 Applicable discard criteria

For each rope - regardless its intended use - the discard criteria should be based on an estimation of the loss in metallic area due to broken wires, wear, loose wires and corrosion, and should be in accordance with the values given in the relevant standard for the rope being assessed.

The loss of metallic area must be calculated over the different stated reference lengths for each of which a limiting area loss is proscribed. The importance of the reference length and the associated maximum loss of metallic area are evident from the values listed in Table 4:

Class of rope	**Reference length**	**Maximum permissible loss of metallic area**
Locked coil ropes	200 x d	10 %
	30 x d	8 %
	6 x d	5 %
Stranded ropes	500 x d	25 % (1) , 40 % (2)
	30 x d	10 %
	6 x d	6 %

Table 4: Discard criteria according to EN 12927.

(1) as required in current standard EN 12927-6. (2) as required in pr-EN 12927 chapter 7.3.

Interpretation of the different reference lengths:

- The *short reference length* for stranded wire ropes corresponds to approximately one rope lay length, or to the double lay length of a wire in a strand (6 x d ⇒ ≤ 1 x λrope or ~ 2 x λstrand).
- The *short reference length* for locked-coil carrying ropes corresponds to approximately 2/3 of one rope lay length (6 x d ⇒ ~ 2/3 x λrope).

In a tensile test, the rope would probably break at this point, and the breaking strength would be reduced by the percentage of the loss of the cross section. This criterion is specifically intended for the assessment of any local damage which has been identified.

- The *medium reference length* for stranded wire ropes corresponds approximately to four rope lay lengths, and correspondingly to ten lay lengths of a wire (30 x d ⇒ ~ 4 x λrope or ~ 10 x λstrand).

- The *medium reference length* for locked coil track ropes corresponds to approximately three rope lay lengths (30 x d ⇒ ~ 3 x λrope).

A redistribution of the tensile load between broken and unbroken wires, depending on the prevailing conditions, cannot be assumed over a reference length of 30 x d. For this reason, it should be assumed that the loss of metallic area calculated over this reference length approximately corresponds to the actual loss of breaking strength!

- The *long reference length* for stranded wire ropes corresponds to approximately 70 lay lengths, and correspondingly to 170 lay lengths of a wire (500 x d ⇒ ~ 70 x λrope or ~ 170 x λstrand).
- The *long reference length* for locked coil track ropes corresponds to approximately 20 rope lay lengths (200 x d ⇒ ~ 20 x λrope).

Due to the fact that the force in a broken wire will recover with distance from the break by means of friction, no reasonable objective correlation between loss of metallic area and loss of breaking strength can be made. This criterion is more powerful as a tool to evaluate the current general state of a rope and to assess the progression of damage, in particular damage due to fatigue.

5.2.1 Importance of maximum permissible loss of metallic area:

Each reference length is associated with a corresponding limiting loss of area. This loss represents the sum of the damage reducing the metallic area of the rope. In addition to wire breaks, inner (fretting) and the outer wear are to be identified and quantified as well. Therefore it is the sum of all the area loss by whatever mechanism in the reference length that must be evaluated.

5.2.2 Additional discard criteria / limits:

In addition to discard criteria specified in terms of loss of metallic area, other criteria should be considered, some of which are listed in Table 5:

Usage	Criteria
General	Maximum allowed visible wire breaks in a rope which is only visually inspected
Stranded rope	More than 50% of the external wires in a strand are broken Maximum allowable diameter reduction of stranded ropes Maximum allowable lay length deviation of stranded ropes
Locked coil ropes	Two broken adjacent z-shaped wires within a lay length (including situations where there is a single intact shaped wire in between the two broken wires)
End fixings	A single wire break or any sign of visible corrosion within one lay length of an end fixing
Splice	Maximum allowed diameter decrease within the splice (in the

	area of tucks and tuck tail ends)

Table 5: Non-exhaustive list of additional discard criteria.

Any other special requirements specified by authorities, manufacturers, etc. should be taken into account as well.

5.2.3 Discard criteria according to the ANSI standard

Part of rope	Reference length	Maximum permissible loss of metallic area
Whole rope	6 x d	7.5 %
	30 x d	10 %
One strand	6 x d	25 %
NOTE: When calculating the number of broken wires corresponding to the specified maximum loss in metallic cross sectional area, the results will be rounded down to the next whole number of wires. See Annex B for examples of how to calculate the number of broken wires allowed.		

Table 6: Discard criteria according to ANSI B77.1-2011.

The main differences between the EN standard and the ANSI standard shown in Table 6 are:

- the ANSI standard does not differentiate between stranded ropes and locked coil ropes for discard criteria,
- the ANSI standard does not specify discard criteria for a long reference length,
- the ANSI standard allows a higher permissible loss of metallic area over the short reference length (6xd),
- the criterion for a single strand is described in the EN standard as an additional discard criterion and states a maximum limit equivalent to 50% of the outer wires of one strand.

5.3 Development of the damage

Every rope has a limited lifetime. In order to ensure continuing rope safety after the detection of any relevant local damage, or general fatigue distributed through the whole rope loop, an evaluation of any further development of the damage is necessary.

5.3.1 Development of locally limited damage

For damage found in a locally limited area, understanding the cause is an essential requirement for assessing any future development. Without this knowledge, a serious assessment cannot be made.

For any locally limited damage the objective should be to eliminate or greatly reduce the cause. By elimination of the cause of the local damage, the future rate of its development can be expected to be approximately similar to that caused by general fatigue of the rope.

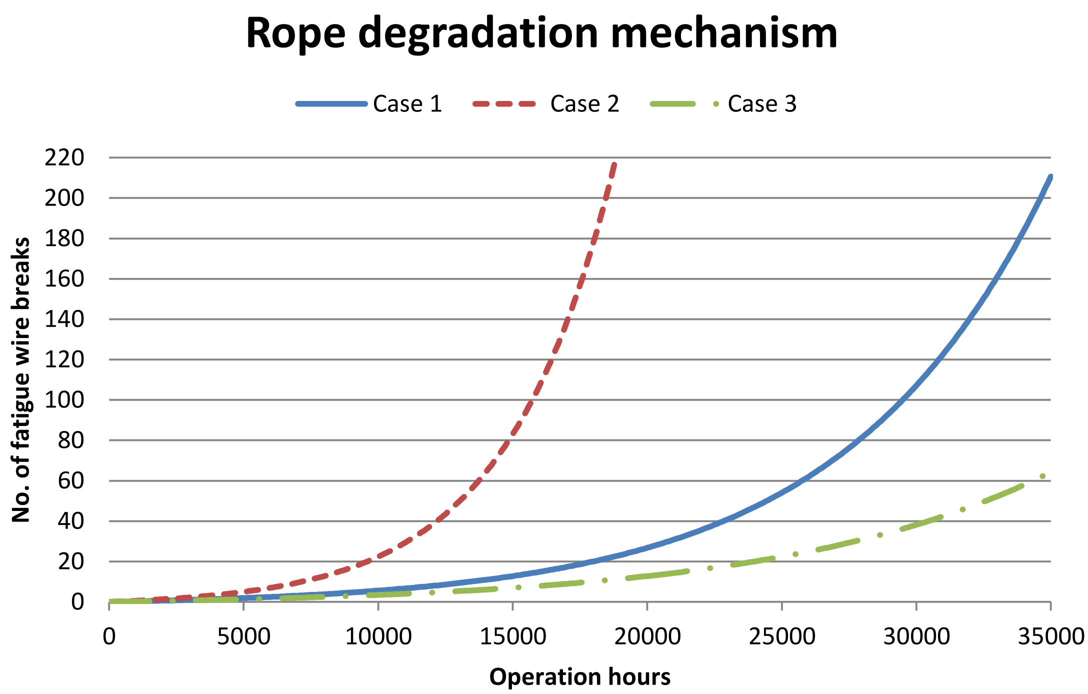


Figure *34*: Damage development (linear scaling).

5.3.2 **Development of distributed damage due to fatigue**

Rope damage resulting from fatigue usually follows an "exponential" pattern. The time-based degradation of a rope depends strongly on the operational conditions which must be considered in conjunction with the expected lifetime of the rope in order to determine the appropriate MRT testing intervals.

Figure *34* and Figure *35* show three different examples of ropes having different rates of degradation for which the explanations could be:

- Case 1: ropes that are used under normal stresses and conditions in accordance with the requirements of the EN standard,
- Case 2: ropes that are influenced by damage, for example through contact with some fixed structure,
- Case 3: ropes that are used under optimized conditions which, as claimed, in the EN standard, can give enhanced service life.

The development of the number of wire breaks can be determined by means of at least three different counting methods. Therefore scatter due to changes in boundary conditions must always be considered.

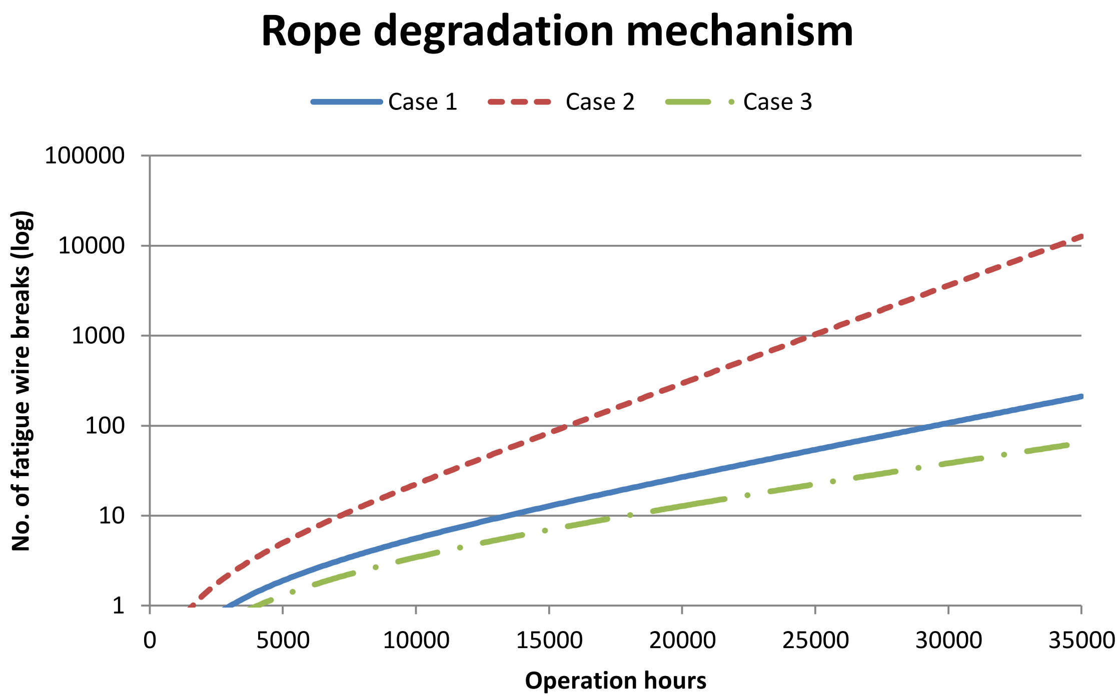


Figure *35*: Damage development (logarithmic Y-axis).

The reasons for the exponential growth of rope damage as a result of fatigue are:

- weak wires start breaking first, then as the number of bending cycles increases, the probability of failure for all the wires in the rope also increases,
- tensile load is transferred from broken to unbroken wires,
- there is an acceleration in the rate of failure of unbroken wires due to the progressively higher stress,
- changes of relevant conditions (e.g. the state of lubrication).

5.4 Development of the number of wire breaks

As already stated, every rope has a limited lifetime. In order to ensure continuing safety of the rope and its termination or splice, an evaluation of any further development of the damage, including definition of subsequent inspection intervals, is necessary following the detection of any relevant local damage or general fatigue distributed through the whole rope loop.
The objective in this case is to ensure that the relevant discard criteria are not exceeded during the time period until the next inspection (visual or MRT).
Therefore, it is necessary for rope users to collect all the information needed to schedule the right time for replacement of the rope.

5.5 Procedure to be followed when reaching the discard criteria / limits

If the values for the maximum permissible loss of metallic area or any other discard criteria are reached:

- the rope must be replaced, or
- the damage needs to be assessed by a competent person, who determines the further procedure. The competent person (a rope specialist) decides whether repair (maintenance / monitoring) is possible and determines the appropriate timescale.

5.6 Sources for discard criteria

The following sources for discard criteria need to be considered:

- national regulations (e.g. regulatory authorities)
- specification of the manufacturer / supplier (operating and maintenance instructions)
- requirements postulated by standards such as:
  - EN 12927
  - ANSI B77.1 - 2011
  - CAN-CSA Z98-07
  - Etc.

6 Test reporting and MRT data management

Summary: *The test report serves as a basis for the operator's maintenance duties (repair, replacement, visual inspection) between two MRT's. It is also the minimum base reference for a magnetic test carried out subsequently by another MRT inspector. In general (if not otherwise required) only the operator receives the test report. Therefore, the information in the report must be as precise as possible. Existing standards do not adequately specify all the requirements for MRT-test reporting necessary for their comparison. The additional guidelines in this chapter address this omission.*

A steel wire rope is a time-limited component. For this reason, the simple determination of its current state to ensure safety is not sufficient. Furthermore, it is necessary to know the history (e.g. the wire rope log), the development of its condition over time, and to consider its use in the actual installation, in order to determine test intervals correctly. For this reason it is necessary to be able to compare results from different testing laboratories.

This can only be assured if certain recommendations are respected and enforced.
In general, all records of rope testing must be retained for the whole lifetime of a rope. Since this period can be very long, special recommendations apply since reports, recordings and important communications between companies testing the same rope must be shared.

6.1 Test reporting

The following international standards contain examples of requirements for test certificates or reports:

- EN 12927,
- EN ISO / IEC 17025, § 5.10,
- EN 1020,
- etc.

Unfortunately these regulations do not meet all the requirements necessary for the comparison of MRT-test reports.
To trace the history of the condition of a rope the test report should provide, in priority order, the following information:

- Information regarding the rope construction such as: type and direction of lay, number of wires, wire diameters, strand diameter, metallic cross-section of each wire, wire coating, metallic cross-section of the rope, nominal diameter and nominal lay length.
- A precise designation of the rope tested and specific areas considered, such as a splice.
- Specification of the magnetization unit, the test coil(s), the testing speed, the test wires, and the recording unit and for a digital recorder, if appropriate, the software version, and the settings. The dimensions of calibration wires should also be reported.
- Testing conditions:
    - weather and lighting conditions,
    - speed or range of speeds,
    - rope condition (clean, dirty, dry, lubricated, etc.).
- Results of the MRT analysis including:
    - number of indications,
    - number of loose wires,
    - other degradation identified such as corrosion, inner and outer wear, lightning strike damage, etc.,
    - measurements of geometric parameters (diameter and lay length) indicating the position at which each measurement was made,
    - the estimated loss of metallic area for any damage detected with a record of the corresponding reference length.

- Display of measured values for the free area and the rope splice:
  - free rope length: the position of local damage referenced to a suitable fix-point must be reported when, typically, the loss of metallic area at this point is at least 50% of the discard criterion,
  - splice:
    in general the splice area should be divided into the following regions, indicating the number of knots and tuck tail ends:
    - knots (± 4 x d)
    - tuck tail ends (± 4 x d)
    - strand insertion parts
    - middle part of the splice (if any).
- Part of rope on the roller chain:
  - a description of the method used to determine which part of the rope is on the roller chain, and which is thus exposed to bending/pulsating stresses,
  - the part of the rope subject to bending and pulsating stresses which has been tested must be identified, and the test method which has been used specified. It is recommended that justification is given where any individual areas could not be verified, and in such cases both the compensation measures adopted and the results, should be reported.
- The locations and types of damage that need to be monitored by the operator between this and the next MRT should be described accurately.
- The results of the current and previous test should be presented in the report in a chart to show the evolution of the rope condition.
- The actual state of the rope should be assessed: this includes in particular a statement as to whether the rope area / areas tested comply with the legal requirements in force at the time the test was performed.
- The period till the next MRT should take place, and its respective date, must be stated.
- Any measures necessary to maintain safety, to be taken by the operator between this and the next MRT, must be clearly specified. Any such specification must include an indication of the required timing.

6.2 MRT data management

It is essential that any documents and recordings are fully traceable throughout the service life of the rope. It should be clear as to who is responsible for assuring the traceability and storage of MRT data. It is necessary that, upon request of the service operator, at any time, these recordings can be provided to another testing laboratory conducting subsequent tests. For the long retention periods necessary, a storage location must be selected to ensure there can be no damage to the documents.

In order to establish reliable traceability of the MRT report and the associated measurement data, it is recommended that any testing laboratory runs an approved Quality-Management System.

7 Hazards and personnel requirements

***Summary**: When performing an MRT test there is a potential hazard for injury to personnel, mechanical damage and failure of the test itself. The risks associated with magnetic rope testing are discussed in this Section.*

For reasons of clarity, hazards are divided into the two following subject areas:

- hazards which can lead to a failure to identify rope defects,
- hazards which can cause damage or injury during the MRT test.

The list of potential hazards is not exhaustive. One of the most important requirements to achieve a good outcome of an MRT test are the qualifications of the inspector. For this reason a list of requirements for the knowledge and skills of an inspector is also given.

7.1 Hazards which can lead to a failure to identify rope defects

- Defective design of the MRT instrument itself, preventing it from performing the functions required for the inspection;
- Inadequate device sensitivity: for example, because the strength of the magnets in a device may have been reduced, or even lost altogether, after they are subjected to mechanical shock;
- Malfunction of the MRT instrument during the inspection: for example, electromagnetic fields in the test environment can create perturbation in the measured MRT signals;
- Inability of personnel to perform the inspection properly;
- Omissions or inaccuracy in the inspection report;
- Incorrect calibration of the MRT system;
- Inspection conditions (for example speed, rope diameter) which are not appropriate for the test equipment;
- Not performing the MRT over the full length of the rope.

7.2 Hazards causing damage or injury during an MRT test

Most common problems regarding personnel and equipment which have the potential to cause damage or injury are a result of one, or a combination, of the following:

- insufficiently trained inspection personnel;
- insufficient physical fitness of the personnel;
- contact of personnel with:
  - the moving rope,
  - moving or rotating components;
- contact of the testing equipment with:
  - towers,
  - ropeway carriers or grips,
  - ropeway structure,

- rope or strand damage,
- protruding shaped wires,
- multiple broken round wires,
- protruding or broken shaped wires or strands,
- deformed or broken splice strands or knots,
- improper geometry of the MRT magnet in relation to rope and splice;

- the MRT magnet breaking loose due to being inadequately secured;
- malfunction of the MRT equipment (opening or lifting functions);
- communication failures between the personnel involved;
- human error;
- failure of the installation control system ;
- insufficient space to install the MRT equipment;
- insufficient work platform for the inspector;
- improper handling of the device during setup or removal due to a strong magnetization force.

7.3 Requirements for the MRT inspection personnel

Where there are no explicit regulations, EN 12927 may be considered as an example of MRT personnel responsibilities. To carry out the MRT tests independently, an inspector has to be able to perform the following activities and needs the knowledge and skills listed below:

Physical capabilities:

- to set up the instrument,

- to perform the tests.

Basic knowledge:
All inspection personnel need a comprehensive knowledge of ropeways, their specific hazards, and the safety instructions for working on a ropeway.

Knowledge of ropes and specific skills:
- knowledge of the type and function of the ropeway on which the rope being inspected is installed,
- the capability to perform an immediate visual inspection of the dubious zones of the rope, and making measurements such as rope diameter, lay length, etc.,
- the ability to perform an immediate visual inspection of a splice,
- the ability to recognize the type and function of a rope, and to understand their modes of deterioration,
- the ability to understand the splicing method, its shortening and the method of repair.

Knowledge of the test equipment, the test procedure and the assessment of failures in a rope
- the ability to record the test results,
- understanding of the limitations of application of the testing method,
- understanding of MRT standards and specifications, and the ability to translate them into practical testing procedures adapted to the actual working conditions,
- the ability to prepare written test instructions,
- knowledge of how to perform the in situ test set-up and calibrate the instrument.

Specialized knowledge of the assessment of failures in a rope
- to be able to classify the results in terms of written criteria,
- to report the results briefly and precisely,
- have a thorough experience and training in the use of MRT,
- to choose the best technique for the test method to use,
- to be able to interpret and evaluate results, including recommendations for future inspection intervals in terms of existing standards, codes and specifications,
- to be able to recommend the use of additional non-destructive tests,
- have a general familiarity with other NDT methods.

Special knowledge as preparation for the performance of an MRT test

Personnel involved in the MRT inspection of a rope should review

- the ropeway's "recognized procedure for MRT testing" (if such exists);
- the rope design and history;
- the ropeway profile and structures;
- the operation of, and protocol for, the ropeway control and communication systems; and the rescue procedures for their own safety.

8 Conclusions and prospects

The reader may recall the questions posed in the introduction on their feelings about MRT, whether they understand it and how much it can be trusted. Try now to think how far you would set the marker towards one of the two extreme answers that were suggested. Now that you – hopefully – have learnt more about MRT, the next question may be the important one:

Are you tempted to think that you can practice MRT on your own ?

8.1 Effective but not easy !

Over a period of many years the reliability has been demonstrated of the magnetic method for testing wire to identify degradation and to assess its progression. But, inspection of a rope using MRT must be performed by well-trained MRT inspectors. As the rope is an intrinsic element in an MRT device it is always a part of the test rig: it is therefore not straightforward to compare MRT devices simply in terms of their internal design characteristics. This is why it is crucial to consider an MRT system in terms of a triangle of efficiency which has at its apexes "rope", "device", "inspector". MRT inspectors must learn how to recognize wire breaks or other defects from MRT signals, and must continuously retrain themselves to improve their knowledge by performing tests on reference ropes which have known defects. Because a wire break may be located in a part where there are various other rope defects, interpreting a wire break signature from the MRT signal may not be obvious and requires real experience on the job. But it is still safe to assume that the occurrence of peaks of any shape is the reliable underlying physical basis of rope inspection using MRT. Therefore MRT inspections must be performed in conjunction with visual inspection. Previous MRT records are often of great help in making an accurate diagnosis by following the development of rope damage from test to test.

8.2 Issues and main known limitations ?

A number of questions and issues are being raised by MRT device designers, inspectors and ropeway operators:

- Some limitations are direct consequences of the magneto-inductive principles and of the device design, such as, for example, the difficulty of obtaining a suitably high and constant magnetization in the measuring coil area, to minimize the role of stray fields or self-induction in the coils. Note that MRT devices should satisfy the recommendations given here.
- Other problems are associated with the testing conditions on a ropeway. Examples of such issues include:
    - the use of an inappropriate coil diameter in relation to the diameter of the rope being tested;
    - an unsuitable test speed that may distort the magnetic flux distribution in the measuring section;
    - proximity to metallic material such as a tower, saddle or roller chain area, that is likely to disrupt the MRT signal.
- Wire break analysis is not a straightforward task with the result that less defects than expected may be found in an internal post-mortem rope examination. For example, the rope ground signal can seldom be separated from clean wire break signatures thus complicating the MRT signal. A wire break signature may be identified as a single wire break, a double break, or more, when there are several peaks overlapping. Such problems become critical for ropes approaching the end of their lifetime which are old, worn and corroded.

MRT inspection has limitations regarding the identification of internal defects such as for instance when a rope is subject to stress corrosion cracking. The whole industry must be concerned by the Schilthorn incident [11] as an example of this issue. In such difficult cases, additional investigations may be usefully performed to evaluate the true condition of a rope. Some innovations are discussed below which have the potential to fill the gap.

8.3 Future work and innovation

Innovative concepts are currently undergoing trials, for example to improve MRT device capabilities, or to provide novel signal processing tools, which can help to ease an MRT inspector’s job.

- 3D high resolution MRT device

The blindness issue of MRT analysis applicable to multiple poorly-separated wire break signatures can sometimes be overcome by the use of a 3D high-resolution MRT device that can, in theory, distinguish several wire breaks spread over the rope cross section. The 3D high-resolution prototype could be the forerunner of the next generation of MRT devices.

- Neural network classifier

An MRT analysis strategy developed in Switzerland [10] uses neural networks to identify anomalies embedded in MRT signals. The procedure involves training a neural networking architecture using a set of known MRT patterns matching, for example, single or double wire breaks. Once the learning phase is stabilized, a pattern matching search strategy is established with the neural network able to recognize similar patterns within rope test signals. This approach is proving to be both consistent and robust.

- Wavelet analysis

The wavelet approach, which is comparable to a mathematical microscope, can be used to analyse MRT signals both as an alternative to current methods or as a complementary tool. The concept involves scanning an MRT signal to highlight patterns that resemble wire break signatures. This innovation seems robust and promising, for example, in the differentiation of poorly-separated wire break clusters, and in extracting information on wear and corrosion from the rope ground signal.

A wavelet framework service featuring specific wavelet wire defect patterns, called "Wirelet", is currently being developed to assist MRT inspectors in the analysis of complex MRT signals.

8.4 Summarizing MRT

Magnetic rope testing can the compared to a chain with three links:

Device:	The MRT device and sensors must be of a high quality design capable of providing optimal rope testing conditions...
Operation:	Rope tests must be carried out by a trained inspector under optimum operational conditions....
Signal analysis:	MRT signal analysis must be performed by a skilled inspector, preferably with the support of dedicated signal processing tools and backed up by visual verification of any MRT anomalies.

In most circumstances MRT effectiveness is guaranteed when all these three links are properly connected. But note that magnetic rope testing which is particularly for the assessment of the internal condition of a rope must be complemented by periodic visual inspection.

9 References

[1] C. E. McCann and R. Colson, "Device for the determination of area loss of wire ropes and cables and similar objects". German Patent No. 175895 Kl 42b Gr. 10, 1906.

[2] R. Woernle and H. Müller, "Meßspule für mit Gleichstrom betriebene Vorrichtungen zur magnetischen Prüfung (Feststellung von mechanischen Zerstörungen) von Stahldrahtseilen". German Patent No 758730, 1937.

[3] R. V. Baud, "Die Kontrolle von Stahldrahtseilen mittels magnetischer Pruefgeraete," *Schweizer Bergbahnen, Oberseeverlage Siebnen.,* 1959.

[4] J. Stachurski, R. Martyna and E. Kalwa, "Use of Hall-effect-sensors for detection of different rope faults," *OIPEEC Bulletin,* pp. 139-147, 1981.

[5] C. Chaplin, I. Ridge and A. Tytko, "Measurement of abrasive wear on wire ropes using non-destructive electro-magnetic inspection," *OIPEEC Bulletin,* vol. 78, no. 679, pp. 67-80, 1999.

[6] M. Dohm, "An evaluation of magnetic rope testing instrument defect detection capabilities, particularly in respect of low rotation, multi-layer rope constructions.," *OIPEEC Bulletin,* vol. 78, no. 681, pp. 37-62, 1999.

[7] J. Nussbaum, Zur Erkennbarkeit von Drahtbrüchen in Drahtseilen durch Analyse des magnetischen Störstellenfeldes, PhD dissertation, IFT Universität Stuttgart, 1999.

[8] A. Haller, "Neue Erkenntnisse über die Seilquerschnittsmessungen / New Methods of Measuring the Cross-Sections of Ropes," *ISR Internationale Seilbahn-Rundschau, Issue 3,* p. Bohmann Verlag Wien, 1984.

[9] A. Tytko and T. Golosinski, "Magnetic rope examinations: definition of rope lay length through LF signal analysis," *OIPEEC Bulletin,* vol. 76, no. 669, pp. 11-20, 1998.

[10] S. Messmer, IWT Institut für Werkstofftechnologie AG, "Today's Wire Rope Testing," Wallisellen, 2012.

[11] G. Oplatka, G. Piskoty and M. Zgraggen, "Track rope incident at the Schilthornbahn," *OIPEEC Bulletin,* no. 782, pp. 181-186, 2006.

10 Glossary

Back Iron : metallic part used to close the magnetic flux circuit.

(Rope) Ground Signal / envelope : General magneto-inductive signal caused by the actual state and geometry of the rope being inspected. Signals for identifiable defects (like wire breaks) project above the ground signal.

High-resolution testing : A sensor head consisting of a circumferential array of Hall effect sensors making it possible to identify the position of a defect, especially used for track rope testing on former tower-saddle areas after relocation of the rope.

Leakage field / Stray field : Part of the magnetic field which the rope and especially defects scatter into the surrounding space. This field component is monitored by the LF sensor coil or Hall effect sensor.

LF coil : Sensor for monitoring changes in the leakage flux crossing a reference surface, typically in the radial direction.

Magnetic bar : Tube used as a robust casing, housing the brittle solenoid material and back-iron elements.

Metallic cross-section of the rope : Sum of the total area of ferritic wire-cross sections.

Magnetic flux density : The level of magnetic excitation which is achieved in a test device which indicates the maximum metallic cross section of rope which can be inspected.

MRT device : Same as MRT apparatus, instrument, machine, unit, test head...

MRT inspector / personnel : Individual(s) responsible for MRT testing, wire break analysis and reporting.

Relative signal density : Statistic diagram showing the relative distribution of signal amplitudes over the whole measured length.

Test calibration : Calibration test of MRT device consisting in correlating the area of an added wire marker attached to the rope surface, with the resulting voltage amplitude induced in the measuring coils.

Test head : MRT apparatus including its main frame, magnets, back iron, sensors and guide system.

Wavelet : (literally "little wave") a type of mathematical function widely used in modern signal processing theory to enable extraction of the instantaneous time-frequency features of a signal.