Today's Wire Rope Testing

After the sudden failure of all external wires of the track rope B of the cable car Mürren - Birg without any - by the means of non destructive testing (NDT) - detectable damage, the quality of wire rope testing has been „under suspicion". The report of the Swiss Investigation Bureau for Railway, Funicular and Boat Accidents (UUS) shows clearly that the type of damage of the track rope induced 25 years before the failure, could not be detected by the magneto-inductive tests as postulated by the regulations. It seems to be useful, therefore, to outline the potential and limits of the magneto-inductive wire rope testing procedure (MRT).

Inhalt

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1. Introduction

On the December 29th 2004, all external wires of the track rope B of the cable car Mürren - Birg simultaneously broke approximately 60 m below the upper station. Cabin 1 was traveling upwards during this incident and was stopped approximately 200 m below the upper station. This severe incident had to be investigated - according to the legal requirements - by the Swiss Investigation Bureau for Railway, Funicular and Boat Accidents (UUS) of the Department of the Environment, Transport, Energy and Communications DETEC. The course of the incident and the cause of damage have been documented in the report of UUS.

In this report it is particularly mentioned that the initial damage, which finally caused the incident, occurred 25 years ago during relocation of the track ropes, could not be detected by the means of regular magneto-inductive tests. In response to this assessment, doubts arose regarding the reliability of the magneto-inductive rope testing.

Since the summer of 2002 IWM keeps continuously developing the wire rope testing system iCART®. Based on the up-to-date gained valuable information and focused on the information gained from the Schilthorn incident the author analyses the performance of the MRT.

2. Wire rope testing basics

Physical principles

Today wire ropes are usually inspected in Switzerland with two different testing methods: the magneto-inductive test (MRT) and the gamma-ray inspection (RT). In addition to this the operators are supposed to inspect all ropes visually. In cases with justified suspicion on damage of the outer wires of fully locked track ropes, classical magnetic particle inspection (MT) methods were used sporadically.

The time-consuming gamma-ray inspection can be applied only on short sections of a rope - generally only rope sections are gamma-rayed, which are not accessible to a magneto-inductive test. The efficient magneto-inductive examination can be used along the entire rope length, as long as its free of obstacles. The classical MT-testing method requires a metallically bright cleaning of the rope surface and is therefore limited to small rope sections.

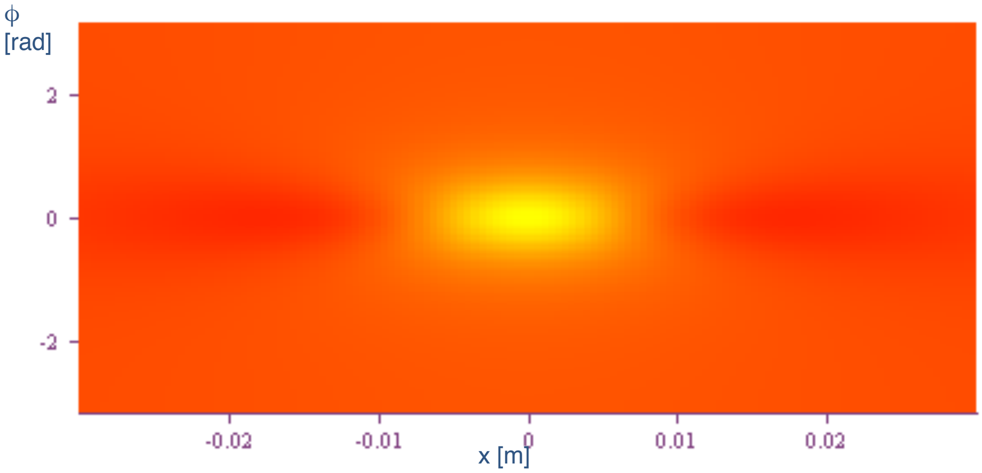
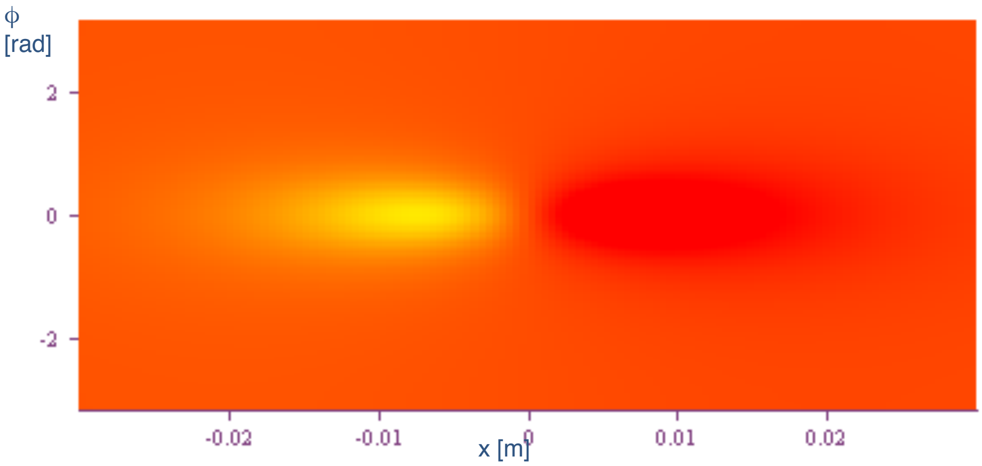
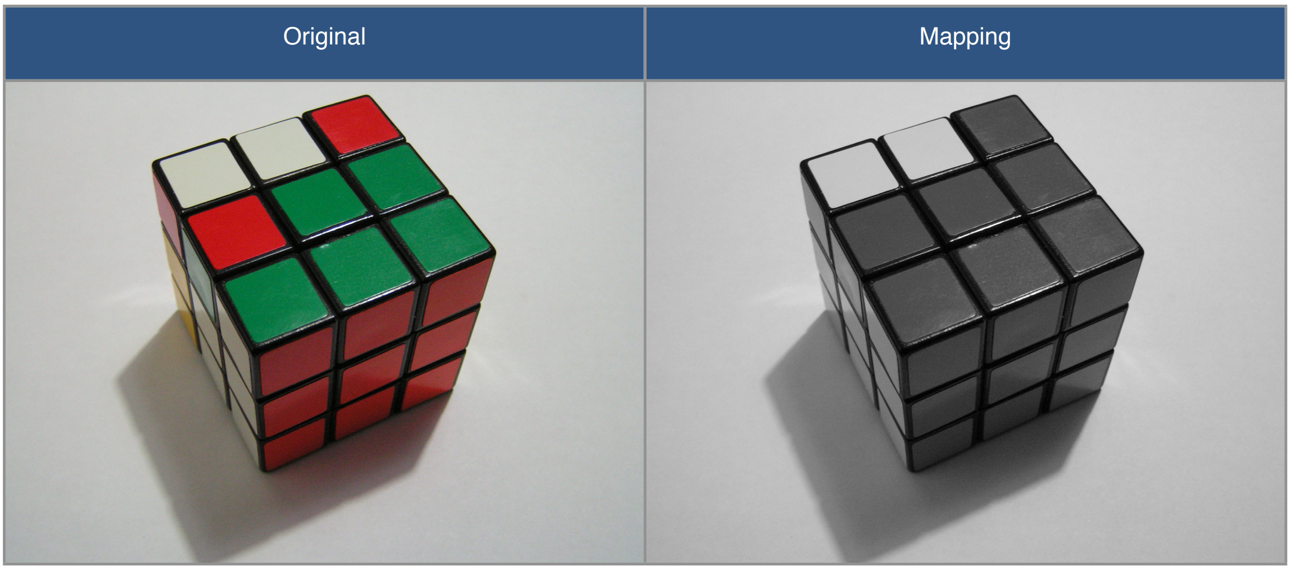
Comment	Magnetic leakage fields of a broken wire in a track rope
Axial component	
Radial component	

Fig. 1: Leakage fields of a typical interior wire break with an aperture of 5 mm at the position of the coils of our testing instrument. The strength and the direction of the leakage fields are color-coded. With the axial leakage field the yellow color means a component in field direction, the red color a component against the field direction. With the radial leakage field the yellow color means a component outward, the red color a component inward. The horizontal axis of the picture is the rope axis, the vertical axis goes toward rope extent.

The magneto-inductive rope testing is based on a systematical registration of the magnetic leakage fields around a rope (figure 1). A wire rope will be magnetically saturated by the means of permanent or electric magnets. If a wire is broken between the two poles of the magnet, a typical leakage field will be created which can be measured with different types of sensors:

- The folded LD-coil-sensor (LD = Local default). This type of sensor measures the sum of the radial component of the leakage field over the area of the coil. The LD-coil can be manufactured with two or more segments simplifying its application.
- The so-called LMA-coil. The LMA-coil needs to be wrapped around a rope. The LMA coil measures the change of the axial component of the magnetic flux through the area of the coil. In the case of a magnetically saturated rope, this change is directly proportional to the change of the metallic cross-section of the rope (LMA = loss of metallic area). Some testing instruments contain LMA-coils wrapped around the back path of the magnetic circuit, because this flux is proportional to the flux in the rope as well.
- Hall sensors. Hall sensors do measure directly the intensity of the magnetic field around the rope. This signal is sensitive to faults in a rope as well. The small size of the sensors enables a measurement of the magnetic leakage fields around the rope (picture-giving rope-testing, see Picture 1).

The typical patterns of test data of LD-coils are shown in the following pictures (see pictures 3 and 4). Picture 4 shows the plots of mathematically calculated signal patterns of typical wire breaks and picture 3 shows a part of a wire rope test of an older carrying-hauling rope.



Picture 2: Color photo and greyscale copy of a simple object. The greyscale copy of the photo does not allow any deduction on the original colors of the fields of the ruby cube. The mapping from colors to greyscale is unique, the inversion is not unique.

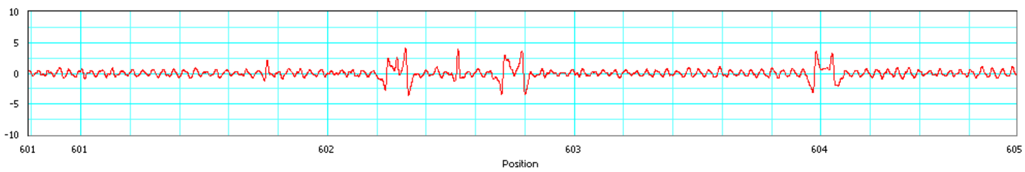
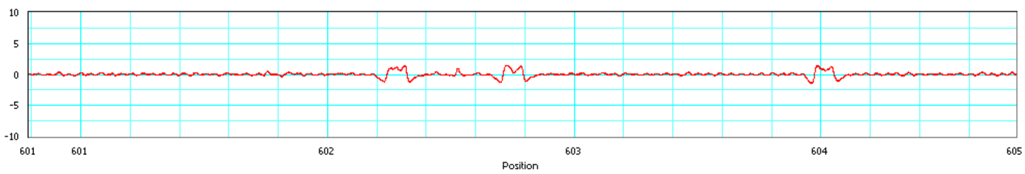
The registration of testing signals during a wire rope test corresponds to a mathematical mapping of a real object on to a testing signal. Like the mapping of a ruby-cube on to a greyscale photo (see picture 2), the mapping is unique. However, the deduction from testing signals to faults is not unique. Like in the case of the ruby-cube where it is impossible to determine the original colors, there are a multitude of possible fault combinations that may lead to a specific testing signal. The mapping procedure from the physical wire rope with faults to the testing signal with indications is so-called „lossy“. This means that some information got lost during the testing procedure and cannot be gained back by any interpretation.

3. Analysis of Testing Signals

Mathematical foundation of wire break analysis

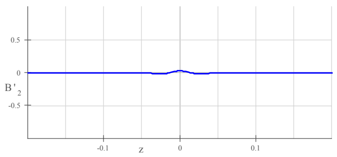
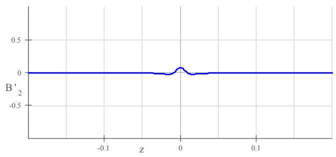
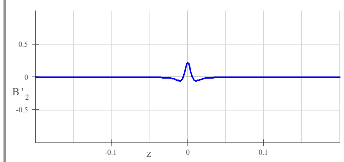
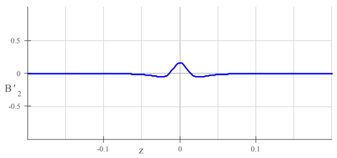
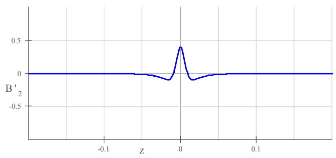
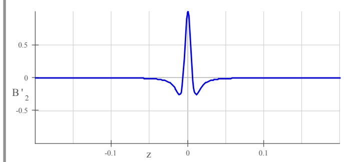
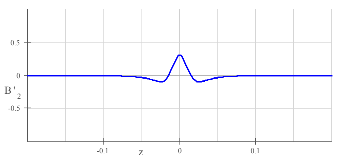
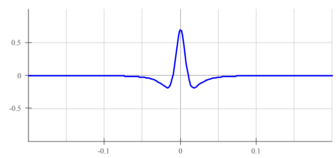
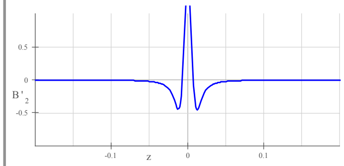
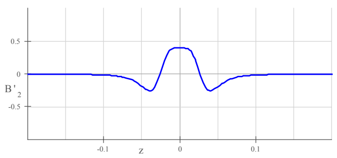
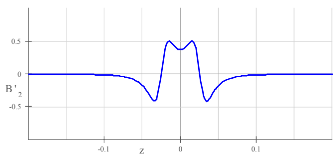
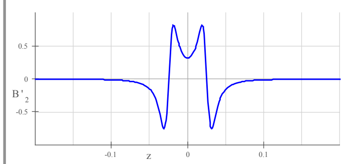
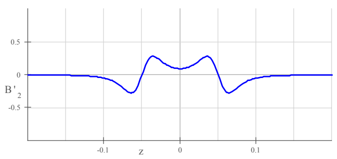
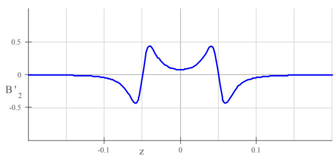
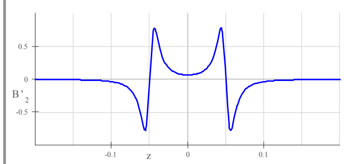
In the mathematical sense the analysis of magneto-inductive wire rope testing signals is the inversion of the mapping of the wire rope onto a testing signal. This inversion, however, includes one intrinsic problem: The inversion is not unique. Picture 2 shows clearly, that the photographic mapping of a ruby cube onto a greyscale picture maps several colors into indistinguishable grey levels. A similar effect in the case of magneto-inductive rope testing may map different fault configurations into indistinguishable wire rope testing signals.

One consequence of this problem leads to the following fact: The interpretation of wire rope testing signals is never unique - there are only fault configurations that are more likely than others. The non-invertible mapping process further influences the analysis process: A standard indication-pattern (search pattern) has to be defined and has to be searched for in the testing signals. In practical applications the positions have to be determined, where the search pattern is significantly present within the testing signal. In signal analysis this procedure is called „pattern-matching“ and it may be performed either by mathematical procedures or intuitively by an experienced user. It is only possible to search for faults that can be standardized and associated with a search-pattern, and their mapping onto testing signals may produce a significant indication within the testing signals.

Comment	Diagram
Signal coil 1 [V]	
Signal coil 2 [V]	
	0.2 m/div

Picture 3: Signals of a wire rope test with LD coils. During the analysis process the search patterns of picture 4 must be fitted into the signal. Please remember the difference between the signal of coil 1 and coil 2: The distance between the outer coil 2 and the rope is much larger than the distance between the inner coil 1 and the rope. The signals, therefore, are much smaller and their resolution is significantly lower.

In the case of a magneto-inductive wire rope test with LD coils only fast and step like differences in the rope cross-section can be standardized. Corrosion and wear of ropes may produce any variation of cross-section and, therefore, cannot be standardized and associated with a search pattern. The classical wire rope testing procedure can reliably detect wire breaks, but is not capable in detecting and quantizing any other type of damage reliably.

Gap	King wire (only track ropes)	Inner wire break (first layer of round wires)	Outer wire break
1 mm			
5 mm			
10 mm			
50 mm			
100 mm			
	50 mm/div	50 mm/div	50 mm/div

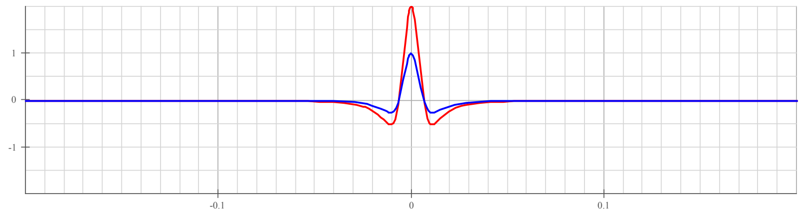
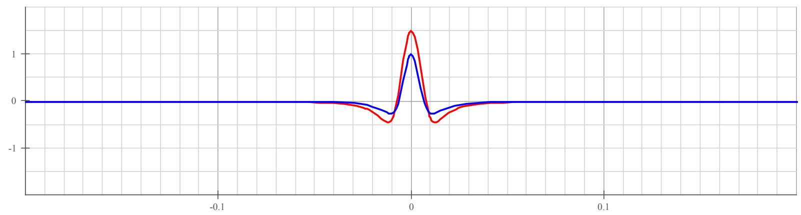
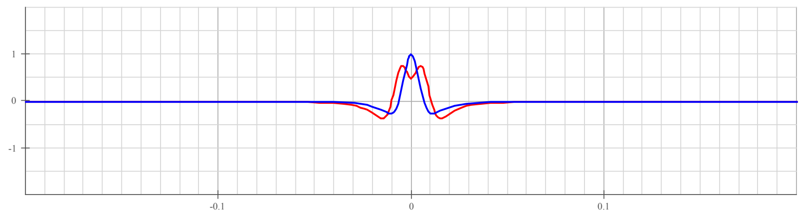
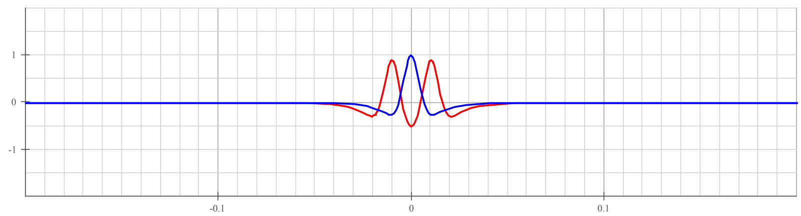
Picture 4: Variations of the search patterns in function of the distance of the fracture faces of a wire (gap) and the position of the wire in the rope.The patterns have been evaluated for 40 mm wire rope and a fault in a 3 mm wire[1,2], the choice of the sensors correspond to our testing instruments. The horizontal axis corresponds to the rope direction, the vertical axis corresponds to the amplified voltage of the LD-coils. The patterns have been calculated by the dipole method (Nussbaum [4], adaption to our testing instruments by the author.).

One important question concerns the resolution of the testing method. This question can only be answered if all testing parameters are known. The choice of testing instruments and recording devices may influence the resolution of the testing instrument as well. To overcome these problems, the results in the following section have been derived from „synthetical" signals and an ideal registration device. The signals may be magnified without limitations. The synthetical signals correspond approximately to the signals of our testing heads. Picture 5 shows testing signals of two wire breaks with a gap of 5 mm and a variable distance between the two wire breaks. The picture indicates clearly the variation of the testing signals with increasing distance between the two wire breaks.

[1] Stranded ropes do generally not contain a king wire.

[2] The cross-section of outer wires of track ropes are significantly larger than the cross-section of inner wires. The indications of wire breaks of outer wires are, therefore, 3 to 4 times larger as shown here.

With minimal distances of approximately 10 mm the signal will show a saddle at the peak level. This is a clear sign of two wire breaks.

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

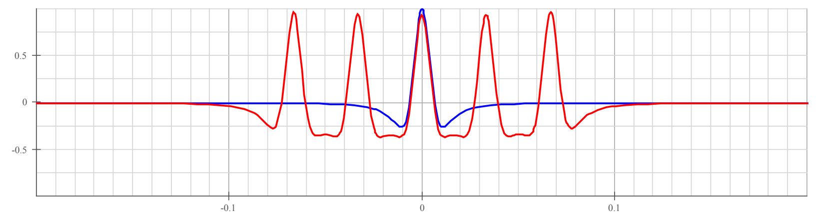
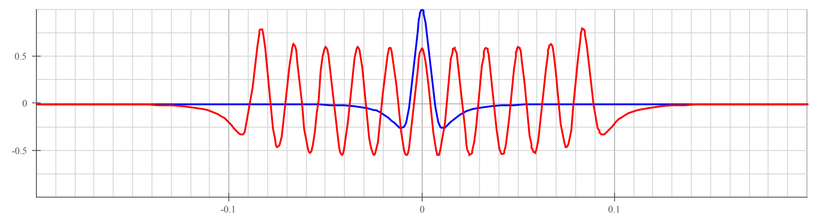
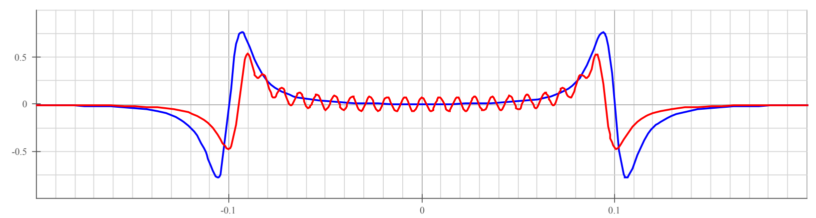
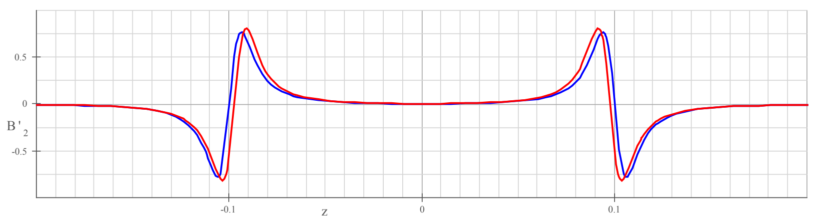
Picture 5: Demonstration of the resolution of the magneto-inductive wire rope testing with LD-coils. The blue line shows the signal of a single wire break, the red line the signal of a double wire break with distances of 0 mm, 5 mm, 10 mm and 20 mm between the two wire breaks. An experienced tester will recognize two wire breaks from a minimal distance of approximately 10 mm. An experienced tester may recognize two wire breaks at the same position as well, because of the height of the peak. Calculation with dipole-method [4]

Another effect of the classical wire rope testing with LD-coils will be demonstrated with the following example: In a short section of a cable several wire breaks have been developed during the last years of operation (up to 20 wire breaks per 10 cm, with a gap of 5 mm between the fracture faces). So many wire breaks within a short distance exceed the resolution of the classical wire rope testing methods. Picture 6 shows the testing signal (calculated, without signature). With 41 wire breaks in the distance of 5 mm the signal almost corresponds to the signal of a missing wire on the distance of 0.2 m. The wire breaks in the middle of the damaged region will no longer be shown individually. Due to imperfections in the distribution of the wire breaks, a tester may observe a modified rope signature or individual peaks. The loss of cross-section will be under-estimated anyway.

These examples leave only one open choice: A development of damage between two wire rope tests as demonstrated must be prevented under all circumstances. If the resolution limit of the testing instruments is passed between two tests, misinterpretations may be the result, leaving the tester no chance to recognize his fault.

Alternative testing methods play a key role in avoiding misinterpretations: A visual inspection will obviously show the difference between a missing wire and a large damage with numerous wire breaks within a short distance. This is also the case for gamma-ray controls: Because these tests are based on different physical effects, they do not have the same limitations, so there is a good chance to recognize faults.

All documents of earlier tests, including diagrams, should be consulted during the analysis. This is the only way to judge the evolution of damages. The earlier diagrams may also contain hints, whether a damage could have passed the resolution limit or not. A test report is not sufficient to avoid misinterpretations.

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

Picture 6: Calculated test signal of a damaged region of a wire rope (5 to 41 wire breaks in a distance of 0.2 m, red line). The blue line shows a wire break signal with a 5 mm gap in the upper two diagrams and a wire break signal with a 0.2 m gap in the lower two diagrams. The testing instruments cannot resolve 41 wire breaks in 0.2 m. An experienced tester will expect a missing wire on a distance of 0.2 m and he will generally not recognize the potential risk of the damage. Calculations with dipole-method [4]

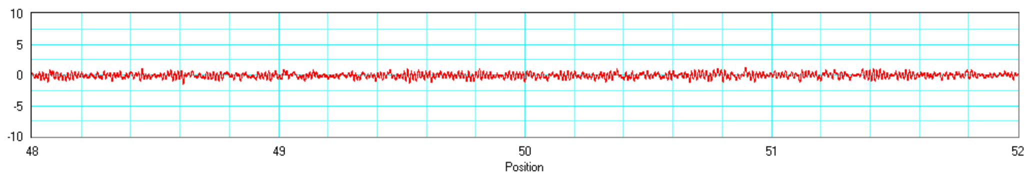
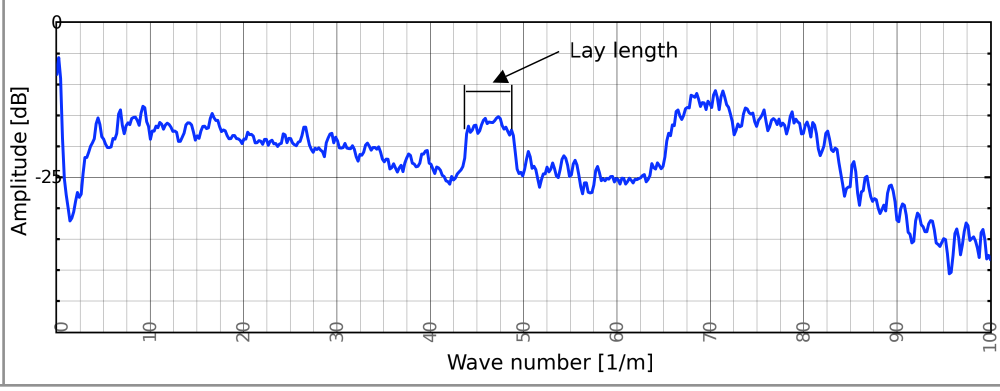
4. Noise and “Signature”

The signature of a wire rope

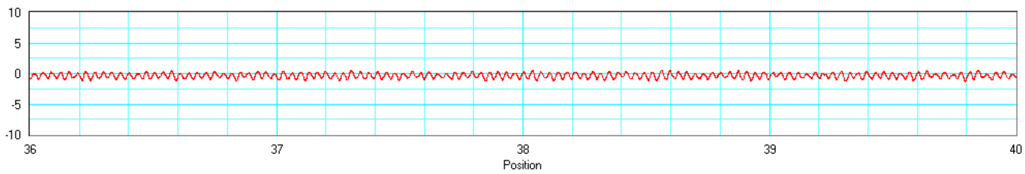
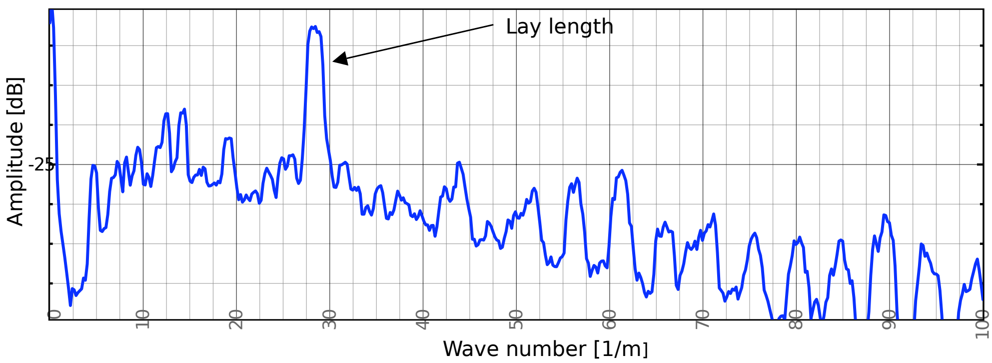
The magneto-inductive wire rope test produces a so-called signature beside the indications of faults in the rope. The signature is coupled in a complicated manner with some basic features of a wire rope. The signature of a stranded rope contains, for example, information about the actual lay length of the rope (see pictures 7 and 8). This relationship can be made visible by a frequency analysis of the test signal. It is even possible to determine the lay length of a rope accurately with a specialized frequency analysis.

If strands of a wire rope begin to touch, notches begin to develop in the outer wires of a strand. Each of these notches produces a small wire break signal, together they produce a characteristic signature signal typical for older ropes (picture 7).

New track ropes produce almost no signature signal - their testing signal is an almost straight line. Older track ropes produce a signature signal related with inner wear, because the high pressure in a track ropes cause notches in the inner wires.

Comment	Diagram
Test signal coil 1[V], (clipping)	
	0.2 m/div
Power-Spectra (Maximum values over the whole length of the rope)	

Picture 7: Signature of an older haul rope with significant wear. The signature is irregular and contains high frequencies. The frequency content has been made visible by a Fast Fourier Transform (FFT). The maximum values of the power spectrum have been recorded over the whole rope length. The plateau in the middle is related with the lay length of the rope, resulting in lay length values from 123 mm to 135 mm (measured 124 mm to 126 mm). The rise in the higher frequency range is caused by notches in the outer wires of the strands.

Comment	Diagram
Test signal coil 1[V], (clipping)	
	0.2 m/div
Power-Spectra (Maximum values over the whole length of the rope)	

Picture 8: Signature of a new haul rope. The signal is almost sinusoidal. The frequency analysis by FFT is shown below. Peak values over the whole rope length have been collected and plotted. The peak is caused by the lay length of the cable, resulting in lay length values from 207 mm to 214 mm.

Every testing signal contains noise beside rope specific signatures. These disturbances may be caused by:

- The movement of the testing head on the rope. Because of the lay length of each cable, testing heads may have a tendency to twist around the cable axis periodically. These twisting vibrations influence the testing signal;
- Rope vibrations - they may disturb the movement of the testing instruments and they may enlarge the noise level in the testing signal;
- Touches between rope and testing instruments may produce high frequency disturbances;
- Various electrical disturbances caused by ground loops or bad grounding.

Most of the above mentioned disturbances may have a strong influence on the testing signals and they may deform the signals until they are unusable - and - they may not be distinguishable from rope signature in each case.

A systematical analysis of the testing signals with respect to signature and noise, nevertheless, should be done. It is very important, that wire break signals shall be detected under any circumstances. Signature signals caused by notches are especially nasty: These signal parts cannot be filtered!

5. Manual and computer based analysis

Differences between a traditional manual analysis and a computer based analysis

Traditionally wire rope testing signals are analyzed manually, even today. IWM operates iCART since 2003, and this system enables an almost fully automized, computer based analysis of wire rope testing signals. From 2000 to 2002 IWM collected a wide experience with traditional manual analysis.

The difference between manual analysis and computer based analysis is smaller than one would expect by a first view. Both types of analysis are based on the same principle: Pattern matching. The difference lays in the quality of the computer based data acquisition. The computer based data acquisition allows to enlarge details of complicated signals after the registration and makes a more profound analysis possible. It is also possible to analyze the registered data with different and independent methods and to compare the results.

In the case of stranded ropes the traditional manual analysis and the automized, computer based analysis show almost identical results in many cases. The advantage of computer based analysis is the judgement of signal quality with respect to wire break detection. A judgement like this might be very difficult in a manual analysis.

Older track ropes often show many indications, which may vary in size and amplitude. With a traditional analysis each indication must be judged with respect to size, pattern and properties of the testing equipment. This is in fact a very difficult and time consuming procedure. Computer based analysis is much faster and more reliable in solving problems like this, but even computer based analysis may produce different results from one test to the other, if the indications are in the magnitude of the resolution. We made some tests with the variation of the internal trigger level of iCART: A 10% increase in the internal trigger level may double the number of indications taken into account in a wire rope test and the same occurs vice versa.

iCART by itself contains two completely independent pattern matching systems and the results of both systems will be compared systematically. In the case of stranded ropes the two systems usually stay synchronized, whereas in the case of track ropes the results of the two pattern matching systems may differ significantly.

These differences may astonish a testing engineer, but they reflect only the fact of existing uncertainties depending whether an indication corresponds to a wire break or not. Depending on the size and the pattern of an indication it is more or less likely whether an indication marks a wire break or not.

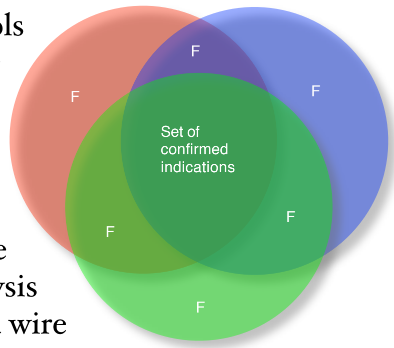
With traditional manual analysis such differences come up, if a testing signal has been analyzed by more than one engineer.

6. Uncertainties of Measurements

Estimation of the reliability of test results

For the estimation of the reliability of rope testing three aspects should be considered:

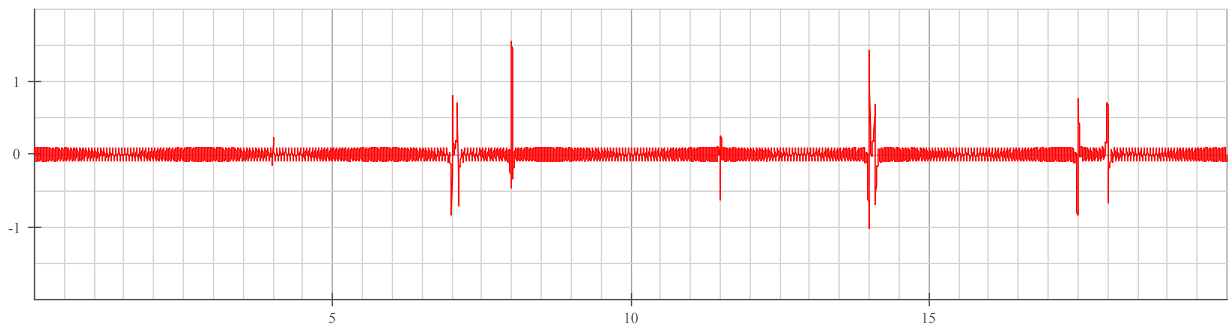
- The uncertainties of the analysis itself - it is essential to perform two completely independent analyses to judge this point;
- The uncertainties in the measurement and recording of the wire rope test;
- The uncertainties in the position measurement.



The uncertainties of the analysis may be described with the tools of the set theory. Every completely independent analysis i produces a set of indications A_i (see table 1). In an ideal case each analysis would deliver the same set of indications. In practical applications some differences may arise: We call the set of indications which are contained in every of the completely independent analysis the „set B“ of the „confirmed indications“. The „set F“ of the indications which are not contained in every analysis we call the „set of questionable indications“. The uncertainty of a wire rope test increases with the number of questionable indications.

The uncertainties in measurement and recording may have different sources:

- The uncertainties of the position of the rope in the testing head may influence the size of the indications, this influence may be strong as the size of indications vary with the square of the distance of the fault to the coil;
- The uncertainties in the measurement itself, this influence factor is usually small (below 1%);
- Other factors.



0.5 m/div																	
Analysis 1		❶			❶	❶			❶		❶	❶			❶		
Analysis 2					❷	❷			❷			❷			❷		
Analysis 3					❸	❸					❸	❸			❸		
Comparison		☺			☻	☻			☺		☺	☻			☻		

Table 1: Three completely independent analyses of the same testing signal. The indications found during one analysis are labeled with the number of the analysis. The lowest line shows the combination of all three analyses. ☻ denotes confirmed indications (4), ☺ denotes questionable indications (3), a total of 7 indications have been found with all three analysis.

The uncertainties in the position measurements have an influence on the calculation of the loss of metallic area for a reference length. The measured reference length may be longer or shorter than the exact reference length and it may contain more or less indications than the exact reference length. Therefore, the calculated loss of metallic area may be larger or smaller than the exact value. The influence of this factor can be easily estimated by modifying the step size of the measurement by the estimated uncertainties of the position measurement.

As mentioned above, the reliability of analysis depends on the rope type and the rope condition. Wire ropes with thick wires (6 x 7, 6 x 17 or 6 x 19) can be tested with a significantly higher reliability than wire ropes with thin wires (6 x 36 or finer) or track ropes. This effect can be explained with the better signal (indications) to noise (rope signature) ratio of cables with thicker wires and in the case of track ropes, the presence of many small indications that won't fit a classical wire break pattern.

One reason of untypical indications may be the complicated fracture faces of wire breaks found in track ropes. Another reason may be soldered wires which are often present in older track ropes. Corrosion also may produce wire break like patterns in track ropes.

7. The „focal point“ of a wire rope test

Indication size, rope design and instrument properties

Up to now only qualitative relationships have been studied within this work. To operate a computer aided system with success, the influence of several parameters must be taken into account. As already mentioned in section 2, the pattern and the size of indications depend on the section of the broken wire, the distance between the two fracture faces, the distance between the fracture face and the coil, the amplification, the width of the coils and other factors.

In the case of stranded ropes it is not unlikely, that the outer wires of the strands are broken, but in the interior of the ropes (at the position where the strands touch). The „focal point“, therefore, should be on outer wires of a strand, in the interior of the rope. Stranded ropes tend to show clearly visible and well formed indications.

In the case of track ropes we often found wire breaks in the most outer layer of round wires. The focal point, therefore, should be set to wire breaks in this layer. This layer often has wires with a relatively small cross-section and the layer has a significant distance to the sensor. In addition to this, wire breaks in track ropes open very slowly because of the internal pressure in these ropes. A track rope may produce, therefore, very small indications so the focus should be set on these small indications.

A testing system should be able to identify small, wire break like patterns when applied to track ropes. But even in the case of stranded ropes small indications should be marked. With settings like these, it should be guaranteed that a testing system may detect all detectable indications.

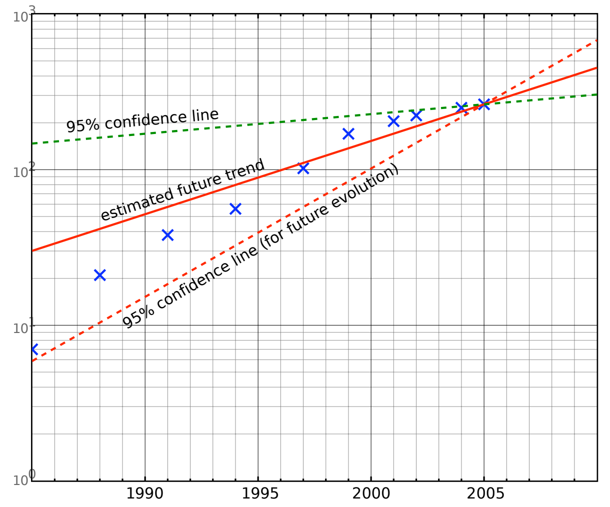
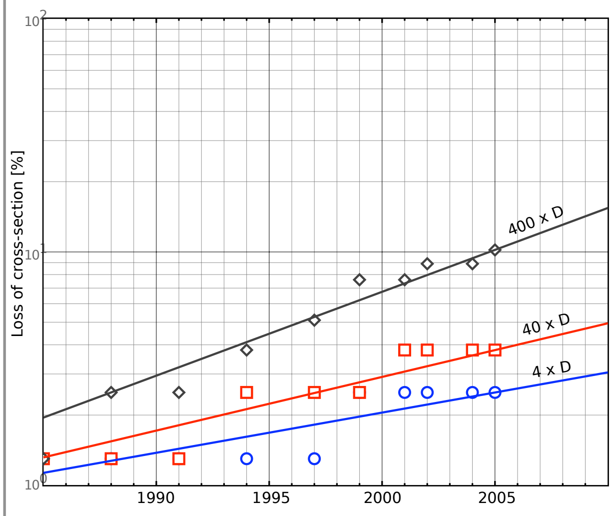
8. Systematical Judgement of the Rope Damage Evolution

The systematical judgement of the damage evolution allows a prediction of future evolution and the inspection period.

The systematical judgement of the evolution of the rope damage is not directly related to wire rope testing, but it is essential to predict the future evolution of a rope. Due to the limits of the magneto-inductive wire rope testing, only the evolution of wire breaks can be assessed systematically.

The evolution of the number of wire breaks due to fatigue in a wire rope generally follows an exponential law. If plotted in half logarithmic scale, the number of wire breaks theoretically follow a straight line (see picture 9). This theoretical relationship has been validated in many experiments and practical applications.

The allocation of the wire breaks in an equally fatigued rope follows a Poisson distribution. (Feyrer [5]). It is typical for this distribution, that the probability of the occurrence of the next wire break is constant over the whole length of the rope. This distribution has been experimentally validated many times.

Evolution of wire breaks	Evolution of the loss of cross-section
	
Year	Year

Picture 9: The left diagram shows the evolution of wire breaks of haul rope during its life, the right one the loss of cross-section. The solid red line in the left diagram shows the expected evolution of the wire breaks in the future, the dashed red line shows the evolution of the 95% confidence value. The 95% confidence value can be used to estimate the inspection period and the remaining life time of the rope. The left diagram shows the evolution of the loss of cross-section (Beck [6]).

(The 95% confidence value line can be explained as follows: If there are 100 identical ropes with exactly the same evolution of wire breaks in the past, 95 ropes will show an evolution in the future below the 95% confidence line and 5 ropes will show an evolution above the 95% confidence line.)

With the knowledge of the evolution of the number of wire breaks and their distribution along the length of the rope the future development can be predicted systematically. It is important to realize that both parameters are necessary to predict the future development. The evolution of the number of wire breaks is generally easy to evaluate, the distribution of the wire breaks, however, may be difficult to determine. The following example may demonstrate this. In a 40 mm diameter hauling rope of 1 km length there is a section of 100 m length with a stronger fatigue. The evolution of the damage in this section is 10 times faster than in the rest of the rope. Half of the wire breaks lie in the section with the stronger damage mentioned before. A tester has no information about the elevated damage and he finds the following results (Table 2).

To visualize the unequally distributed fatigue, we define an „equivalent damaged length". This parameter can been calculated with the following relationship in mind: For every number of indications and every length it is possible to calculate how many indications should be inside a reference length based on a regular distribution. The reverse question, on how many meters all the wire breaks shall be distributed regularly, to fulfill the results of the tests, can be answered as well. We call this imaginary length the „equivalent damaged length" of a damaged rope. The equivalent damaged length in the above mentioned example is 200 m. The equivalent damaged length is a good measure to demonstrate whether the distribution of wire breaks in a rope is regular (Poisson distribution).

Date of test	Number of Indications (total)	Number of indications (4 x D)	Number of indications (40 x D)	Number of indications (400 x D)	Equivalent damaged length
2000	10	1	1	2	< 685 m

Date of test	Number of Indi-cations (total)	Number of indi-cations (4 x D)	Number of indi-cations (40 x D)	Number of indi-cations (400 x D)	Equivalent dam-aged length
2001	25	1	1	3	< 650 m
2002	50	1	2	6	< 301 m
2003	100	2	3	11	< 247 m
2004	250	2	6	24	< 233 m

Table 2: Evolution of the damage in a hauling rope with a damaged region of 100 m length. The damaged region will be visible for a tester only after quite a large number of wire breaks have been developed. This effect generally prevents testers from recognizing local damages in an early stage. The theoretical equivalent damaged length is exactly 200 m. Calculation after Feyrer [5]

The results of an estimation of the damaged length are clear: The estimated damaged rope length is always longer than the effective damaged rope length (200 m for the above outlined example). The quality of the estimation increases with increasing number of wire breaks. This fact has strong consequences to the any prognosis of the future evolution of damage: Over-estimating the damaged length directly leads to an under-estimation of the predicted rope damage. The shorter a local damage is, the greater is the error of prediction and it gets more and more likely that a tester cannot recognize the real potential of a rope damage.

We call this important effect the „masking of a damage“. The importance of this effect is evident, but we currently cannot estimate its influence on predictions of future evolution of damage.

It is important not to base predictions of future damage evolution on the expected number of wire breaks (also called 50% confidence value). It is much wiser to use a 95% confidence value (or even a stronger confidence value). This guarantees to overestimate the damage evolution in most cases.

With the above outlined methods it is possible to estimate the evolution of damage in a wire rope, as long as the dominant degradation mechanism is fatigue with increasing number of wire breaks. In most moving rope applications wire breaks will develop and, therefore, their future evolution can be predicted with sufficient accuracy. Track ropes generally do not develop wire breaks during a significant part of their life cycle. Within their last period of life they may produce wire breaks and they tend to follow the rules mentioned above. Track ropes on roller chains do develop wire breaks, but they are not regularly distributed. Wire breaks on roller chains often occur in a short length in the region with most bending cycles.

The evolution of damage due to other degradation mechanisms (corrosion, stress corrosion-cracking, wear, etc.) cannot be assessed accurately by the means of the testing methods discussed here and, therefore, their evolution cannot be predicted up to now. In the case of a track rope, for example, the choice of an inspection period and the correct prediction of the time to discard currently remain on intuition.

If the inspection period has been chosen incorrectly, there is an inherent risk of failure of a whole layer of wires of a rope between two inspections. As such an incident cannot be excluded completely even in the case of regular magneto-inductive tests, wire ropes need an extremely conservative safety factor. Current regulations in Switzerland fulfill this criteria for most rope types. Only 6 x 7 Standard ropes and 6 x 15 Seale ropes will break, if the outer layer of wires will fail completely. These ropes are used in Switzerland as haul ropes for cable cars and some types of ski lifts.

9. From Testing to Safety Concepts

Wire rope inspections by themselves do not guarantee safety.

During the last few years there have been several cases where parts have failed despite of regular non-destructive test. In almost none of these cases a faulty test was the reason of an unforeseen failure. Unacceptable treatment of the part during manufacturing or maintenance, an inadequate inspection concept or too long inspection periods are generally the reason for surprises. It is not enough to inspect an important part carefully, it is necessary to make sure, that

- a part can be inspected according to the needs;
- the inspection method is capable in detecting the expected faults of the part;
- during manufacturing, mounting, operation and maintenance no damage will be induced that cannot be detected and judged by the chosen inspection method;
- the pre-damaged part contains enough safety against failure;
- the system that contains the part has some redundancy in the case of an unforeseen failure, where ever it is possible;
- all procedures will be supervised by the operator or the manufacturer.

Only an optimal concept which will be followed can guarantee a long period of operation without unforeseen incidents.

Behind national and international regulations (for example the Swiss federal rope regulations) there is a safety concept for the operation of ropes since many years. This concept guarantees the safe operation of ropes. It does not guarantee, however, that all possible damages can be detected in an early stage. An availability of 100% of a rope way installation is not guaranteed.

Today, the magneto-inductive test is the preferred inspection method in national and international regulations. The test report should contain the loss of metallic area of a rope, including wire breaks, wear and corrosion. It is also necessary to judge the inspectability of a rope.

Concerning the magneto-inductive rope testing this demand is somehow problematic - neither the magneto-inductive test nor the gamma-ray test can detect wear and corrosion reliably and it is, therefore, difficult to estimate the loss of cross-section due to wear and corrosion. There is a method to estimate inner and outer wear based on the geometrical properties of a stranded rope, but this method contains significant uncertainties. In the case of locked coil track ropes no comparable method exists to estimate inner wear.

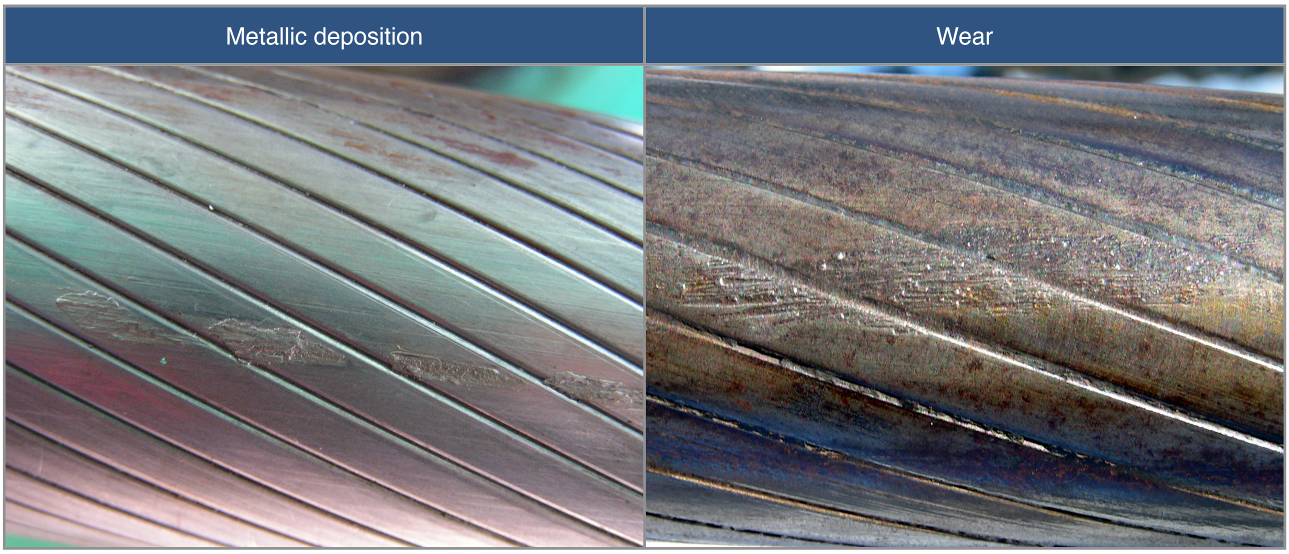
Outer wear and corrosion can be judged, if the damaged parts of the rope have been found. Inner corrosion cannot be judged based on the currently available testing methods. The size of the rope signature may be an indication for corrosion or wear, but it is not possible to correlate this value with the loss of metallic area. And there is absolutely no guarantee, that the state-of-the-art test methods can detect inner corrosion or wear in every case.

Another type of damage - cracks in wires - currently cannot be detected by the magneto-inductive test. This limit of the classical wire rope inspection is well known since a long time. Generally fatigue fractures do not develop at any position of the rope at the same time and the evolution time from first cracking to a fully developed wire break is short compared to the time it needs to initiate a crack. Therefore, it is unlikely that the classical rope inspection method will fail, because there are only a few pre-cracked wires in addition to the already broken - and detectable - wires. The case of track rope B of the Schithorn cable car shows, however, that in the case of a well defined and well distributed pre-damage of the wires the cracks and the following wire breaks may evolve in a very short time. Such a short interval can never be supervised by an appropriate inspection period.

Despite of all disadvantages and limits the classical, magneto-inductive wire rope test is the only method that allows inspection of all wires in the cross-section over the whole length of a wire rope. Most of the other test methods are either limited to outer wires or they are not capable for an inspection of the whole rope length or even show both limitations. These test methods, therefore, can be used in addition to the classical wire rope testing, but not as a replacement.

There have been some efforts to develop methods that are capable in detecting cracks in wires after the case of Schilthorn. The difficulties in an attempt like this are not related to the test methods by itself, they are related to the incredibly difficult conditions of wire rope inspections. Most methods, including the visual inspection, need clean and grease-free surfaces to be applied successfully. Cleaning track ropes according to the needs of most non-destructive testing methods (MT, PT, VT) is a challenging task and, at the moment, is only possible in a very limited region.

Visual inspection is more tolerant than the other testing methods and does not need a completely grease free surface. But the quality of the visual inspection gets considerably better with cleaner surfaces.



Picture 10: Typical damages of track ropes, induced by incorrect shift procedures. Both type of damages cannot be detected by a classical magneto-inductive test, because the change of metallic cross-section is negligible. Both types of damages can be detected by visual inspection. The MT-test of the Z-wires of the left track rope shows several cracks below each piece of metallic deposition. These cracks will grow by stress induced corrosion and the wires will break after some time.

Wire ropes will never be as well inspectable as a special designed part for example in aviation industry. In contrary to classical parts, wire ropes have an inherent high fault tolerance. When used in well designed an correct applications, the high fault tolerance is much more important than the limited inspectability.

Today's inspection methods are highly capable in detecting an supervising the evolution of wire breaks. Track ropes, however, do not show an evolution of wire breaks over a significant part of their life. A systematical prediction of the future evolution and the remaining life period is, therefore, hardly possible. The selection of an inspection period remains on intuition of the tester.

The above outlined requirements lead to the following proposition for a safety concept regarding the operation of wire ropes:

- The currently implemented safety concept should be rethought with respect to the difficult conditions in rope testing and the above outlined uncertainties of rope inspection in general;
- Scientific research should provide approved methods to judge the evolution of damage in track ropes systematically;
- A continuous evolution of inspection techniques should be followed with the aim of elimination the current restrictions. Improved resolution, efficiency, convenience in use are important demands in this field;
- The supervision of works on ropes should be improved. Due to the limited inspection depth of ropes, damages which result from work actions must not remain undiscovered. Profound visual inspections should be carried out immediately after or during rope work.

The key to success lays in improving the quality and the supervision of work on ropes. Damages like the ones of the ancient track rope B of the Schilthorn cable car should not remain undiscovered, because they can hardly detected afterwards and a repair may be impossible or expensive in an advanced stage of damage.

10. Conclusions

This publication outlines the fundamental relationships in magneto-inductive wire rope testing. The mechanisms of detection of faults in a rope are explained and the limitations of the testing techniques are shown. The differences between a manual detection and a machine detection of wire breaks are demonstrated. In comparison with manual analysis, the computer aided analysis of magneto-inductive opens more and advanced possibilities. The test data can be analyzed systematically with respect to signal quality. It is also possible to analyze data with modern digital signal processing methods to show more or less hidden properties. It is, for instance, possible to calculate the lay length of a stranded rope based on the signals of the magneto-inductive test or it is possible to demonstrate the presence of internal wear. But even the most advanced digital signal processing methods have limitations. The traditional wire rope test was invented to detect wire breaks and even with modern methods it is not possible to detect other damages reliable. Wear and corrosion may be detected, but this is not reliable and the extent of these damages cannot be estimated reliably. On the contrary to a manual analysis, measurement uncertainties, for example of the position measurement, must be taken into account in a computer based analysis.

One topic of this publication is the systematical judgement of damage evolution in wire ropes. The evolution of wire breaks is demonstrated with examples and the possibilities of damage prognosis are explained. To achieve a reasonable quality of a prognosis it is necessary to evaluate the increase of wire breaks with time and their distribution along the rope length. It is shown, that local damages can only be made visible in an advanced stage. Therefore, manual and computer aided analysis have an inherent risk of misinterpreting the potential of local damage and to recommend an inappropriate inspection period. The consequences are clear: A small risk of larger damages always remain within an inspection period.

The last part of this publication shows that wire rope inspections by themselves do not guarantee a 100% availability of a ropeway installation. To maximize the availability of a ropeway installation it is necessary to install and maintain a comprehensive safety concept. This concept must include dimensioning, manufacturing, mounting, operation, maintenance and inspection of the wire rope.

A last point of rope safety concerns the safety factors used for dimensioning. The safety factors prescribed by national and international standards guarantee the safety of a rope, with few exceptions even in the case of larger damages. A profound analysis of ropeway systems shows that large safety factors are necessary, inter alia because of the uncertainties of the currently applied test methods. Reducing the currently prescribed safety factors must be questioned carefully.

A future development of the inspection techniques is desirable to improve the availability of ropeway installations, but this subject stays complex. There are several reasons for this fact, one might be the incredible high efficiency demanded from test methods, an other might be the complexity of a rope inspection and a third one the difficult environmental conditions.

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