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Nondestructive Wire Rope Inspection: Detection and Quantitative Characterization of External and Internal Corrosion Pitting and Broken Wire Clusters

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ABSTRACT

Modern wire ropes have a tendency to deteriorate internally, which makes visual inspections ineffective.

Furthermore, although more dependable than visual inspections, the reliability and effectiveness of present electromagnetic nondestructive test methods and practices leave a lot to be desired. For example, the custom of using Loss-of-Metallic Cross-Sectional Area (LMA) alone as a rope retirement criterion can be dangerous and is suspect.

The present paper introduces a new inspection and analysis method that promises to significantly improve this situation.

The concepts of **Signal Fidelity** and **Wire Rope Roughness (WRR)** are introduced and discussed.

Test results from several well-documented rope samples confirm the feasibility and accuracy of the new approach.

INTRODUCTION

The operating safety of wire ropes is adversely affected by several types of rope deterioration. For the purposes of this paper, major deterioration modes can be categorized as follows.

Basic Loss of Metallic Cross-Sectional Area (BLMA):

BLMA is loosely defined as Loss of Metallic Cross-Sectional Area that stays approximately constant and smooth over extended distances (say, greater than one Lay Length) along the length of a rope. While for the purposes of this paper, BLMA is mostly a theoretical concept, for actual ropes this type of damage is usually caused by wear and corrosion assisted wear.

BLMA can be measured – with various degrees of accuracy and resolution – by those electromagnetic wire rope inspection instruments that allow the quantitative characterization of LMA.

Wire Rope Roughness (WRR):

WRR is defined as the aggregate surface roughness of all wires in a rope. WRR is typically caused by and indicates corrosion pitting, interstrand nicking, broken wires and clusters of broken wires. The WRR signal is characterized by small-amplitude and rapid – i.e., high spatial frequency – variations over short distances along the rope.

The method described in this paper extracts two components from the LMA signal that can be analyzed separately to determine and measure BLMA and WRR. This technique will be referred to as "WRR Analysis."

WRR can be detected – albeit with considerable limitations – by the LF (Localized Flaw) signal. This signal is available from present rope test instruments. The usefulness of the LF signal is quite restricted, and it provides only qualitative – and usually very incomplete – information. It does not allow the actual measurement of the extent and severity of WRR.

The WRR signal has some features in common with the LF signal. However, much more useful than the LF signal, it is quantitative and could replace the LF signal. It could then be called *Quantitative LF (QLF)* signal.

WIRE ROPE DETERIORATION MODES OF THE WRR-TYPE [1], [2], [3]

The following examples describe some typical rope deterioration modes of the WRR-type that are the subject of this paper.

Corrosion Pitting

Corrosion is a serious hazard to a wire rope.

Corrosion pitting causes stress concentrations. This kind of corrosion is extremely insidious, as it causes little loss of material with rather small effects on the rope surface, while it damages the deep structures of the metal. The pits on the wire surfaces are often covered by corrosion products.

Corrosion pitting inhibits the free movement of wires and strands, which produces additional stresses in wires. The increased wire stresses combined with the above mentioned stress concentrations can drastically accelerate the development of fatigue breaks.

Corrosion assisted wear can also cause wires to corrode uniformly over their entire surface which may reduce their cross-sectional area and cause loose wires.

The severity of corrosion often varies along the length of a rope. Frequently, corrosion is localized but, nevertheless, dangerous. The extent of corrosion is often difficult to gauge and – as shown by experience – is usually underestimated.

Internal Broken Wires (Single and in Clusters), Inter-Strand and Inter-Wire Wear and Nicking

Many ropes are of the torque-balanced multi-strand type, comprising two or more layers of strands. Figure 1 shows a cutaway section of such a rope. Torque balance is achieved in multi-strand ropes by laying outer and inner strands in opposite directions.

This type of rope construction limits axial rotation of a freely suspended rope under load. In addition, multi-strand ropes offer flexibility and a wear resistant surface profile.

In single fall crane operations the use of non-rotating ropes is mandatory.

However, the wires and strands in different layers of these ropes touch locally and at an angle. Therefore, when multi strand ropes bend over sheaves or on a drum, they are subject to the combined effect of radial loading, relative motion between wires and bending stresses.

Therefore, multi-strand ropes are prone to develop inter-strand nicking (Figures 2 and 3) and internal broken wires (Figure 4). This breakup occurs primarily on the interface between the outer and second layer of strands, usually with no externally visible signs as indicated by Figure 5. The wires in the second layer of strands typically show nicking and breaks caused by a combination of fluctuating axial wire stresses, inter-wire motions and fluctuating radial loads. The broken wires usually show squared-off and z-shaped ends that are typical for fatigue breaks.

FIGURE 1. Multi-strand rope construction

FIGURE 2. Inter-strand nicking

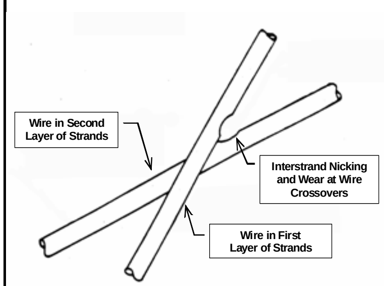


FIGURE 3. Inter-strand nicking

In addition, many multi-strand ropes are subject to corrosive environmental conditions. For example, offshore ropes are either immersed in the sea or continually wetted by salt water spray. In addition, heavy use in a marine environment can displace and degrade the rope lubricant. The combined effects of fatigue, corrosion and lubricant degradation can cause rapid internal deterioration, with no externally visible indications, where there is no effective form of protection. Since deterioration of non-rotating rope is not easily detected, failure of the rope is often unexpected.

FIGURE 4. Broken wires in second layer of strands

FIGURE 5. Typical positions of broken wires in multi strand ropes

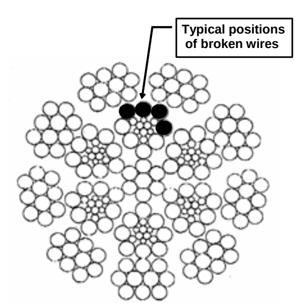
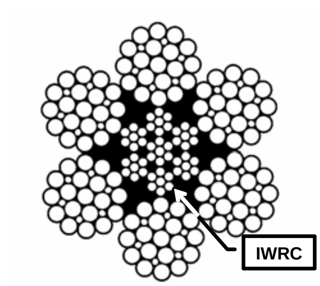


FIGURE 6. IWRC rope construction

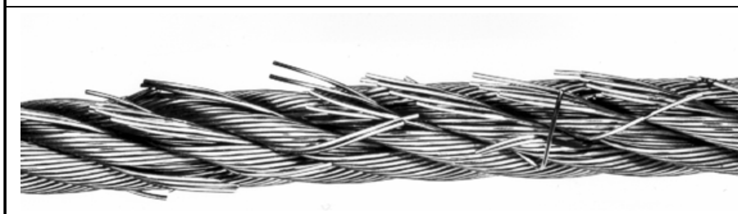


Similar nicking and fatigue patterns occur also in IWRC (Independent Wire Rope Core) ropes. Figure 6 shows a typical cross-sectional diagram of such a rope. For IWRC ropes, the outer wires of the outer strands have a larger diameter than the outer core strand wires. To minimize inter-strand nicking between the outer strands and the IWRC, these ropes are designed such that the wires of the outer strands and the IWRC are approximately parallel. (This is usually achieved by choosing a *lang lay* construction for the IWRC and an *ordinary lay* construction for the outer strands.)

Typically, the wires of the outer strands are well supported by their neighbors while the outer wires of the IWRC are relatively unsupported.

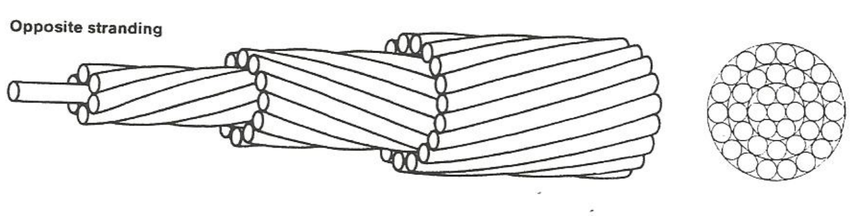
The result of these geometrical features is that, under fluctuating tensile loads, the outer IWRC wires are continuously forced into the valleys between the outer strand wires and then released. This mechanism results in secondary bending stresses leading to large numbers of core wires with fatigue breaks. These breaks can be very close together and can form groups of breaks. Eventually, the IWRC can break, or it can even completely disintegrate into short pieces of wire about half a lay length long. This condition is commonly called *complete rope core failure.*

FIGURE 7. Valley breaks



As the IWRC fails, the outer strands lose their radial support. This allows the wires of the outer strands to bear against each other tangentially. The resulting inter-strand nicking restricts the movement of the strands within the rope. Without this freedom of movement, secondary fatigue breaks in the wires of the outer strands will develop at the strand tangent points. Because these fatigue breaks develop in the valleys between the outer strands, they are also called *valley breaks* (Figure 7).

FIGURE 8. Spiral strand construction



Another example. Spiral strand (Figure 8) is made up of concentric layers of wires, some of which are spun in opposing directions to give the strand a measure of torque balance. Therefore, the individual wires in different layers touch locally and at an angle, and the helical geometry within the layers creates radial inter-layer contact forces. When used in mooring applications, spiral strand is subject to fluctuating loads and, especially, bending. Then, depending on the level of axial tension and radius of curvature, spiral strand is subject to interlayer slippage, which causes axial motion between wires in different layers combined with tension and torque stresses. Therefore, it is to be expected that, as a result of these geometrical features, wires in different layers will develop inter-wire nicking and fretting and, eventually, secondary fatigue breaks.

As an aside, spiral strand is frequently protected by plastic sheathing, which prevents corrosion and corrosion pitting. However, plastic sheathing makes visual inspections ineffective.

VISUAL AND ELECTROMAGNETIC WIRE ROPE INSPECTION METHODS

A general survey of wire rope inspection methods, including their capabilities and limitations is useful in order to recognize shortcomings of present techniques. This comparative review also identifies the open niches that the proposed WRR inspection procedure will fill.

The following is a short discussion of present wire rope nondestructive test methods.

1. A complete wire rope inspection consists of several components. This means, a thorough inspection should, if at all possible, consider all aspects of a rope's condition, including:

   a. The findings of a visual inspection,
   b. the results of an EM rope inspection,
   c. the rope construction,
   d. the rope's operating conditions and related damage mechanisms, and
   e. the history of the rope under test and that of its predecessors.

   In other words,

   - the inspector should use all inspection methods available to him, and
   - he should know in advance what type of rope deterioration he can expect to find.

2. To be useful, inspections should be quantitative. This is true because retirement criteria must be – and usually are – based on quantitative data such as *number of broken wires per unit of length*, *percentage loss of metallic cross-sectional area, etc.*

3. The LMA signal is best suited for the detection and measurement of cross-sectional area loss caused, for example, by corrosion and wear.

   Frequently rope discard criteria specify that a rope must be retired when its percentage LMA exceeds 10-15%. However, if used as the sole retirement criterion, this practice is questionable.

   To quote one wire rope expert [4]:

   > *"We warn strongly against Loss of Metallic Cross-Sectional Area (LMA) measured by a magnetic rope test instrument to be used as discard criterion. In practice, we have had ropes fail under their own weight with LMAs of 3 to 5%. It is indeed a very dangerous practice to discard ropes based on LMA alone as work done by Professor Chaplin of Reading University indicates. A small loss in metallic area of a rope can lead to major reductions in the remaining strength of a rope. Again, from practical experience in the field of NDT and destructive tests of numerous discarded rope samples one must be very, very circumspect in using LMA as discard criterion, especially a 10% LMA."*

4. The LF signal is primarily useful for the detection of single broken wires. However, while often used as a criterion for evaluating the performance of test instrumentation, the detection of isolated single broken wires is meaningless and not important for making rope retirement decisions.

   For example, a typical LF chart recorder signal of a broken wire has a positive and a negative going section. Therefore, positive and negative signal components, caused by closely spaced broken wires in a cluster, have a tendency to and will overlap and cancel. This idiosyncrasy makes it impossible to determine – or even estimate – the number of broken wires in a cluster. This has lead to erroneous LF signal interpretations with associated errors in evaluating the actual rope condition. Therefore, the LF signal is not useful for estimating the number of broken wires in clusters.

5. The detailed detection and quantitative characterization of internal broken wires in ropes with many breaks and clusters of breaks pose problems. Difficulties are caused by the fact that, for electromagnetic wire rope inspections, the indication of a broken wire is influenced by a number of parameters like
   a. broken wire cross-sectional area,
   b. broken wire gap width, and
   c. the position of the broken wire within the cross-section of the rope.
   d. For clusters of broken wires, an additional problem is caused by the fact that the relative position of broken wires with respect to each other along the length of the rope is not known. For example, the gaps of broken wires could be aligned or staggered.
   e. Finally and most importantly, broken wires with zero or tight gap widths are not detectable by electromagnetic inspections because they do not produce a sufficient magnetic leakage flux.

   Considering the above, only an estimate of the number of broken wires is possible.

6. Visual Inspection can detect external deterioration such as external broken wires and external signs of corrosion and wear. Inherently, visual inspection cannot detect internal rope degradation. Furthermore, plastic sheathing makes visual inspections ineffective.

7. Diameter Measurements are mostly useful for the detection of severe internal damage such as total core failure and major internal corrosion.

8. Quantitative methods for evaluating the severity of corrosion pitting and its influence on the condition and safety of wire ropes are presently not available.

9. The present state of the art of wire rope inspection is categorized in Table 1. The table classifies the capabilities and limitations strictly of wire rope testers manufactured by NDT Technologies, Inc.[1] and of visual inspection methods for various types of rope deterioration.

10. The WRR Analysis will provide reliable estimates for the quantitative characterization of corrosion pitting and of clusters of broken wires. As shown in Table 1, this capability will fill an important niche that is not adequately covered by present wire rope inspection methods.

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[1] Rope testers from various other manufacturers have different specifications.

TABLE 1. Present Detection and Quantitative Characterization Capabilities of Electromagnetic Rope Testers Manufactured by NDT Technologies, Inc. and of Visual Inspections

Inspection Method	Corrosion/Wear Detection and Characterization Capabilities	Uniform Corrosion and Wear: External	Uniform Corrosion and Wear: Internal	Corrosion Pitting: External	Corrosion Pitting: Internal
LMA Inspection	Quantitative	feasible	feasible	WRR Analysis (discussed here)	WRR Analysis (discussed here)
	Qualitative	feasible	feasible	WRR Analysis (discussed here)	WRR Analysis (discussed here)
LF Inspection	Quantitative	not feasible	not feasible	not feasible	not feasible
	Qualitative	not feasible	not feasible	feasible	feasible
Visual Inspection	Quantitative	not feasible	not feasible	not feasible	not feasible
	Qualitative	feasible	not feasible	feasible	not feasible
Diameter Measurement	Quantitative	not feasible	not feasible	not feasible	not feasible
	Qualitative	limited feasibility	limited feasibility	not feasible	not feasible

Inspection Method	Broken Wire Detection and Characterization Capabilities	Single Broken Wires, Gap Width Wide (>50 mm): External	Single Broken Wires, Gap Width Wide (>50 mm): Internal	Single Broken Wires, Gap Width Tight (< 50 mm): External	Single Broken Wires, Gap Width Tight (< 50 mm): Internal	Broken Wire Clusters Various Gap Widths: External	Broken Wire Clusters Various Gap Widths: Internal	Broken Wire Clusters Various Gap Widths: Total Core Failure
LMA Inspection	Quantitative	feasible	feasible	limited feasibility	limited feasibility	WRR Analysis (discussed here)	WRR Analysis (discussed here)	feasible
	Qualitative	feasible	feasible	feasible	feasible	WRR Analysis (discussed here)	WRR Analysis (discussed here)	feasible
LF Inspection	Quantitative	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible
	Qualitative	feasible	feasible	feasible	feasible	limited feasibility	limited feasibility	feasible
Visual Inspection	Quantitative	feasible	not feasible	feasible	not feasible	feasible	not feasible	not feasible
	Qualitative	feasible	not feasible	feasible	not feasible	feasible	not feasible	not feasible
Diameter Measurement	Quantitative	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible
	Qualitative	not feasible	not feasible	not feasible	not feasible	limited feasibility	limited feasibility	feasible

Legend: feasible (green), not feasible (red), limited feasibility (yellow)

WRR ANALYSIS

As will be demonstrated by the following examples, WRR is a reliable indicator of the rope condition. Because it is derived from the LMA trace, the WRR is automatically calibrated together with the LMA signal (say, in % of metallic rope cross-sectional area). Therefore, the WRR trace can be used to quantitatively characterize corrosion pitting and external and internal broken wires, including clusters of broken wires. Especially, in the absence of corrosion pitting, WRR Analysis is well suited for estimating the number of internal and external broken wires (single or in clusters).

NDT Technologies, Inc. has recently incorporated WRR Analysis in its NDT_CARE™ (**C**omputer-**A**ided **R**ope **E**valuation) computer program. Hence, this type of analysis is now readily available and can be routinely applied.

LMA Signal Artifacts

The WRR Analysis method extracts the WRR signal from the LMA signal. Compared to the LMA signal, WRR signal amplitudes are usually quite small.

On the other hand, nondestructive wire rope test equipment always introduces – avoidable or sometimes, unavoidable – instrument-specific artifacts into the test signals. While these artifacts represent relatively minor disturbances for the overall LMA signal, their signal amplitudes are of the same order of magnitude as those of the WRR signal. Hence, if not eliminated and/or avoided, they seriously distort the rather small WRR signal, and they will compromise the accuracy and reliability of WRR test results.

For example, low-pass filtering is typically used to reduce inherent noise and to improve the signal-to-noise ratio of LMA signals. However, low-pass filters make inspection results dependent on inspection speed, and they suppress and distort the relatively small indications caused by corrosion pitting and broken wire clusters. These indications always have high spatial-frequency components, and the amplitudes of test signals with high frequencies are drastically reduced by low-pass filtering. Hence, low-pass filtering must be avoided for WRR Analysis.

Other artifacts are introduced by the physics of the data acquisition process. One of these phenomena is called the 'Echo Effect', which can be explained as follows [5].

A particular discontinuity causes its actual indication in the test signal as it passes the sensor-section that is positioned in the center of the test head. Two echoes – with smaller amplitudes than the actual indication – are induced when this discontinuity enters and exits the sensor head. Hence, the 'echoes' occur immediately before and after the actual signal indication. This way, while the echoes introduce measurement errors that are relatively small compared to the LMA signal, they represent a significant distortion for the WRR signal.

The *Echo Effect* is inherently caused by the geometry of the sensor-magnet arrangement – with the sensor section positioned between the two poles of a permanent magnet. This basic design is common to all present-day sensor heads of the hinged clamshell design. Therefore, any of the present sensor heads will exhibit this behavior.

However, the 'echoes' can be eliminated by an *Echo Cancellation* – or *Signal Enhancement* – computer algorithm. This algorithm is described elsewhere [5]. Signal Enhancement allows test signals with exceptional fidelity and resolution.

This added degree of accuracy becomes meaningful if and when WRR Analysis will be used to make rope retirement decisions. Then, the extra precision will become significant for avoiding either premature rope retirement or unsafe operating conditions.

The *Echo Cancellation* algorithm has been incorporated as part of the NDT_CARE™ computer program, and it is now routinely used for analyzing the results of electromagnetic wire rope inspections.

The *Signal Enhancement* algorithm is illustrated as part of Test 2 below.

Test Parameter Sensitivity

The WRR is determined by scanning the rope along its entire length using a sliding window on the rope. The width of this window can be specified by the inspector. Typically, the lay length of the rope under test can be used as window width.

Note that the WRR Analysis shows little or no sensitivity to window width as long as this width is chosen to be approximately equal – within a wide range – to the rope lay length.

EXPERIMENTAL RESULTS

NDT Technologies, Inc. has participated in several Round Robin tests. In the following, results from these experimental inspections will be used to establish feasibility of the WRR method.

These trials and the subsequent analysis of the test data were carried out in three stages.

1. Test data were acquired by using nondestructive wire rope inspection equipment of the NDT_TEST™ series.
2. The ropes under test were destranded after their examination, and the state of their deterioration was verified visually and recorded in great detail. These reports are in the public domain, and they are readily available [6], [7].
3. More recently, a WRR Analysis of the test data was performed.

The correlation of the WRR Analysis results with the actual condition of the ropes under test shows a very close correspondence. This proves the feasibility and the value of the proposed methods.

Test 1: [6]

This WRR Analysis concerns the “Broken Wire Rope Sample” that was tested as part of the Round Robin tests in Bochum (Germany) in 1998.

This is a 48 mm diameter, 15 strand, fishback, low rotation multi-layer rope. A cross-sectional diagram of the rope is shown in Figure 5. The present analysis deals with the inspection of this torque balanced multi-strand rope. This rope – referred to as Rope 1 in the following – had been used as a mine hoist rope on a trial basis and was known to contain numerous internal broken wires and no corrosion along its entire length.

This case study illustrates the use of WRR Analysis for the detection and quantitative characterization of internal broken wires and clusters of broken wires in multi-strand ropes. The task at hand was to determine the number and position of broken wires along the length of the rope.

After the tests, a particular section of this rope was dismantled and carefully examined. This particular visual rope inspection is unique because it meticulously analyses and documents the actual rope condition in great detail. To our knowledge, no other rope has been as thoroughly examined as this one. A complete documentation is presented in the literature [6].

Figure 9 shows a WRR Analysis of the rope under test. This chart shows four traces as follows.

i. LMA(%) – The original LMA trace after Signal Enhancement.

ii. BLMA(%) – The idealized Basic LMA trace without the effects of corrosion pitting and broken wires.

iii. WRR(%) (Wire Rope Roughness) – A quantitative indication of corrosion pitting and broken wires.

iv. Average WRR% – Primarily useful for estimating the number of external and internal broken wires (single or in clusters) per unit of length in the absence of corrosion pitting.

Figure 10 shows the correlation of broken wire estimates – based on WRR Analysis – with the visual broken wire count over 0.2 m intervals along the length of the rope, which has been published in [6] (cf. Fig. 4.2.1.4(b)).

Note that some of the peaks of both curves in Figure 10 do not coincide. This is due to distance measurement errors for the nondestructive inspection. These errors are systematic and cumulative. They can be caused by a slightly oversized or undersized distance counter wheel, slippage of the wheel and many other causes.

Figure 11 shows a comparison of the actual WRR values with a visual count of the maximum number of visual broken wires over 0.1m intervals along the length of the rope as published in the Appendix of Reference [6].

The WRR trace in Figure 11 was adjusted to compensate for distance counter errors. Note that this figure has two distance axes on the top and the bottom of the chart. The axis on the bottom shows the actual distance along the rope as determined during the visual inspection. The top axis shows the rope distance that was measured during the nondestructive inspection. The measured distance axis was adjusted as shown simply by aligning the peaks of the WRR trace with the peaks of the broken wire trace.

After this alignment, Figure 11 shows a close correlation between test results and the actual number of internal broken wires.

There are, however, a number of discrepancies between the test results and the actual broken wire count. These differences can be caused by the fact that the indication of broken wires is influenced by a number of parameters like broken wire gap width, broken wire cross-sectional area, and, most importantly, by the fact that broken wires with zero or tight gap widths are not detectable by electromagnetic inspections because they do not produce a sufficient magnetic leakage flux.

Considering these uncertainties associated with evaluating the effects of broken wires on the LMA signal, and with assessing the effects of inter-strand nicking and internal wear, the accuracy of these nondestructive test results must be considered excellent.

It is even to be expected that the WRR test results, rather than the number of counted broken wires, are a better reflection of the actual rope condition. This is true because, beyond the number of broken wires, the WRR Analysis also reveals and measures other rope deterioration such as interstrand nicking, fretting, wear, etc. In addition, it could be argued that wider gap widths of broken wires indicate more serious rope deteriorations.

Note that, although this rope is in a seriously degraded condition, its LMA trace indicates little change of rope cross-sectional area. Only the WRR Analysis exposes the dangerous state of this rope.

Resolution and Averaging Length. The dictionary defines *resolution* as "*the level of detail that can be distinguished in an image (or a recording)*." In nondestructive testing, the terms *resolution* and *inspection accuracy* are often used synonymously.

In the discipline of electromagnetic wire rope inspection, *quantitative resolution* or *averaging length* (sometimes also called *scanning length*) is defined as the minimum length of a uniform anomaly for which the sensor provides an accurate measurement of LMA [2].

The rope inspection equipment used for acquiring the experimental data of this report – after signal enhancement – offers a *quantitative resolution* of 50 mm.

On the other hand, Appendix 1 of Report [6] lists the number of broken wires in 10 mm intervals along the length of Rope 1. To make the broken wire count commensurate with the quantitative resolution of the test equipment, this data was used to determine the number of broken wires over a 50 mm sliding interval along the length of the rope.

Figure 12 shows the correlation between the broken wire count and the WRR_P values.

Here WRR_P denotes the peak values of WRR. This is an alternative representation of WRR that is used to keep Chart 12 uncluttered.

Similar to Chart 11, distances of the WRR and the broken wire traces were adjusted in Figure 12 by aligning peaks of both traces. This was done by slightly changing the scaling of the *measured distance* axis.

The figure shows a correspondence between the WRR_P trace and the actual broken wire count that is quite remarkable.

Furthermore, similar to Figures 10 and 11, the WRR_P indicates that the rope deterioration in the area around a rope distance of 3.5 to 4.5 m is more serious than indicated by the broken wire count.

This example and the two following tests suggest that ropes should be retired when their WRR exceeds a value of 1% - 2%.

Finally and most importantly, the close correlation between the WRR Analysis and the actual condition of the rope test sample verifies convincingly the value and reliability of the WRR Analysis method.

FIGURE 9. Rope 1, WRR Analysis

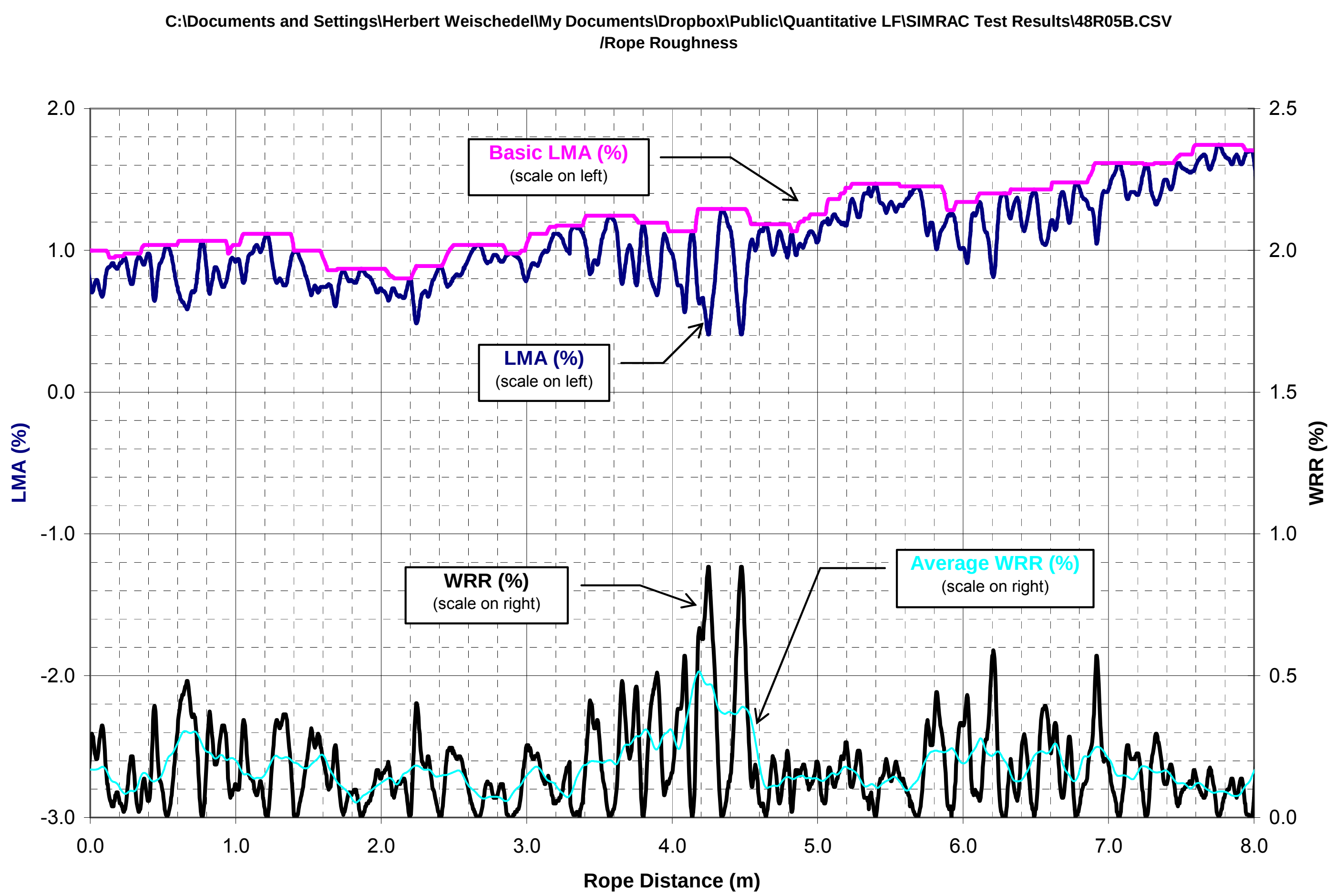


FIGURE 10. Rope 1, actual vs. estimated broken wire count

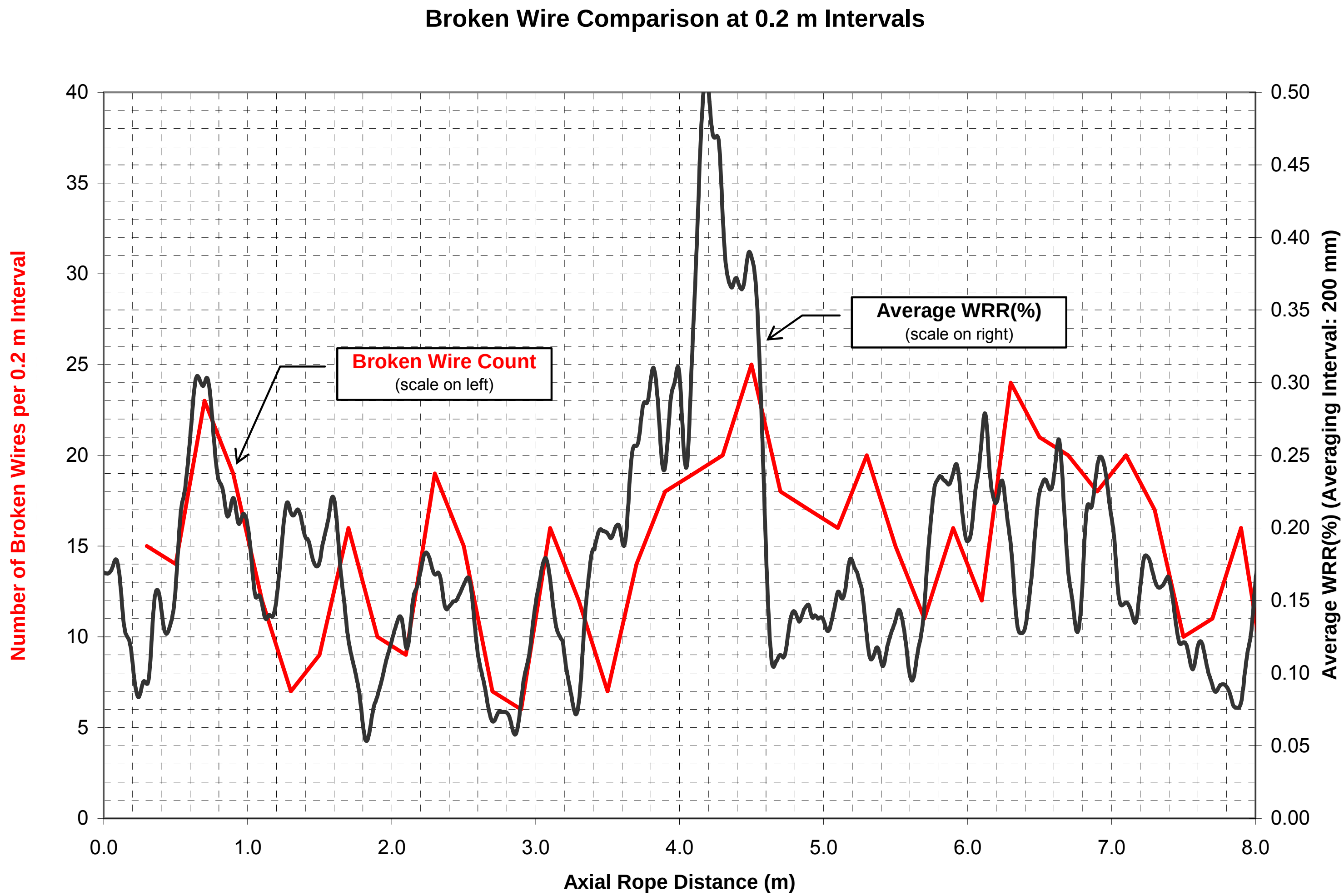


FIGURE 11. Rope 1, comparison of WRR Analysis results vs. actual broken wire count (distance adjusted)

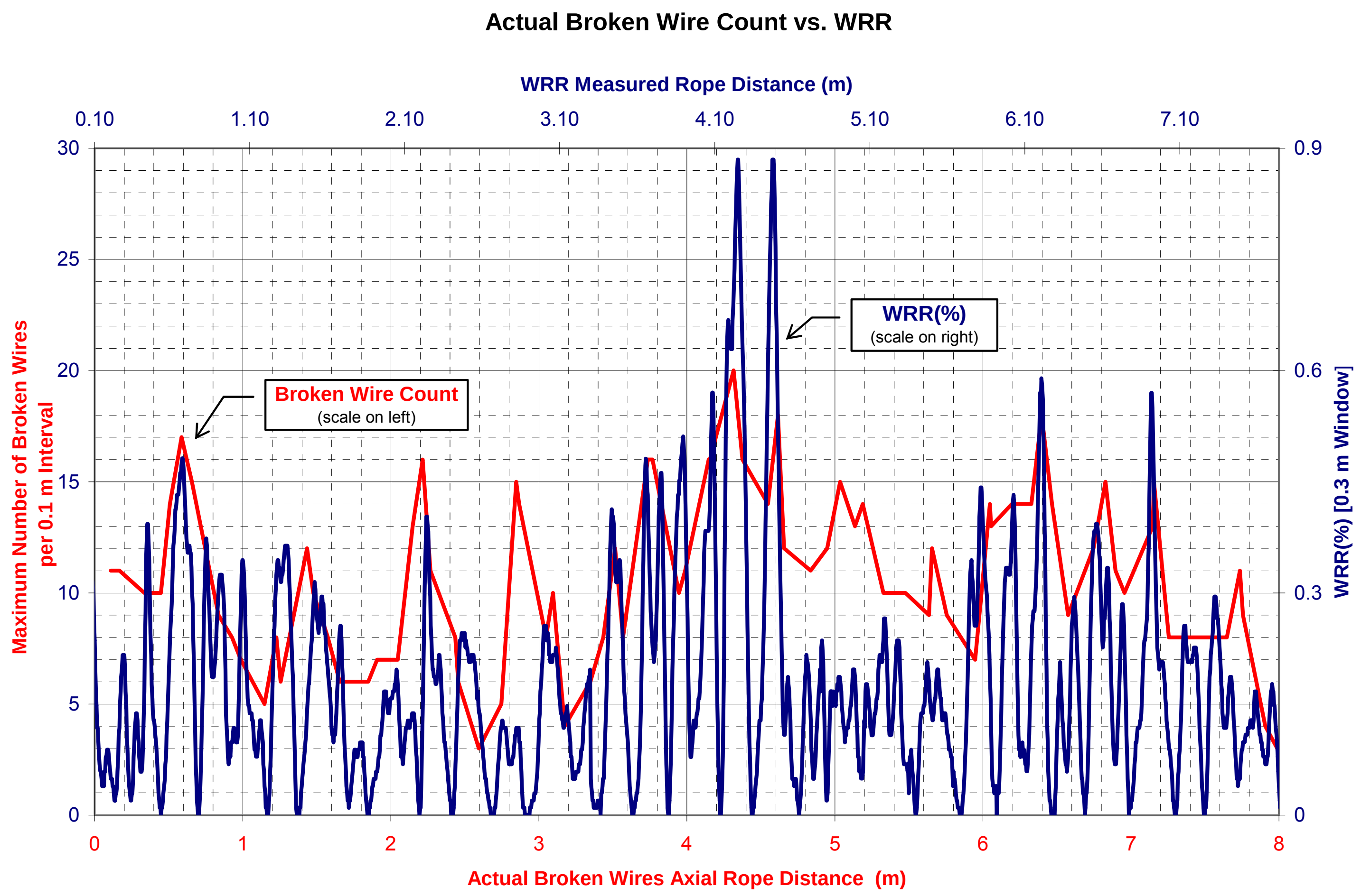
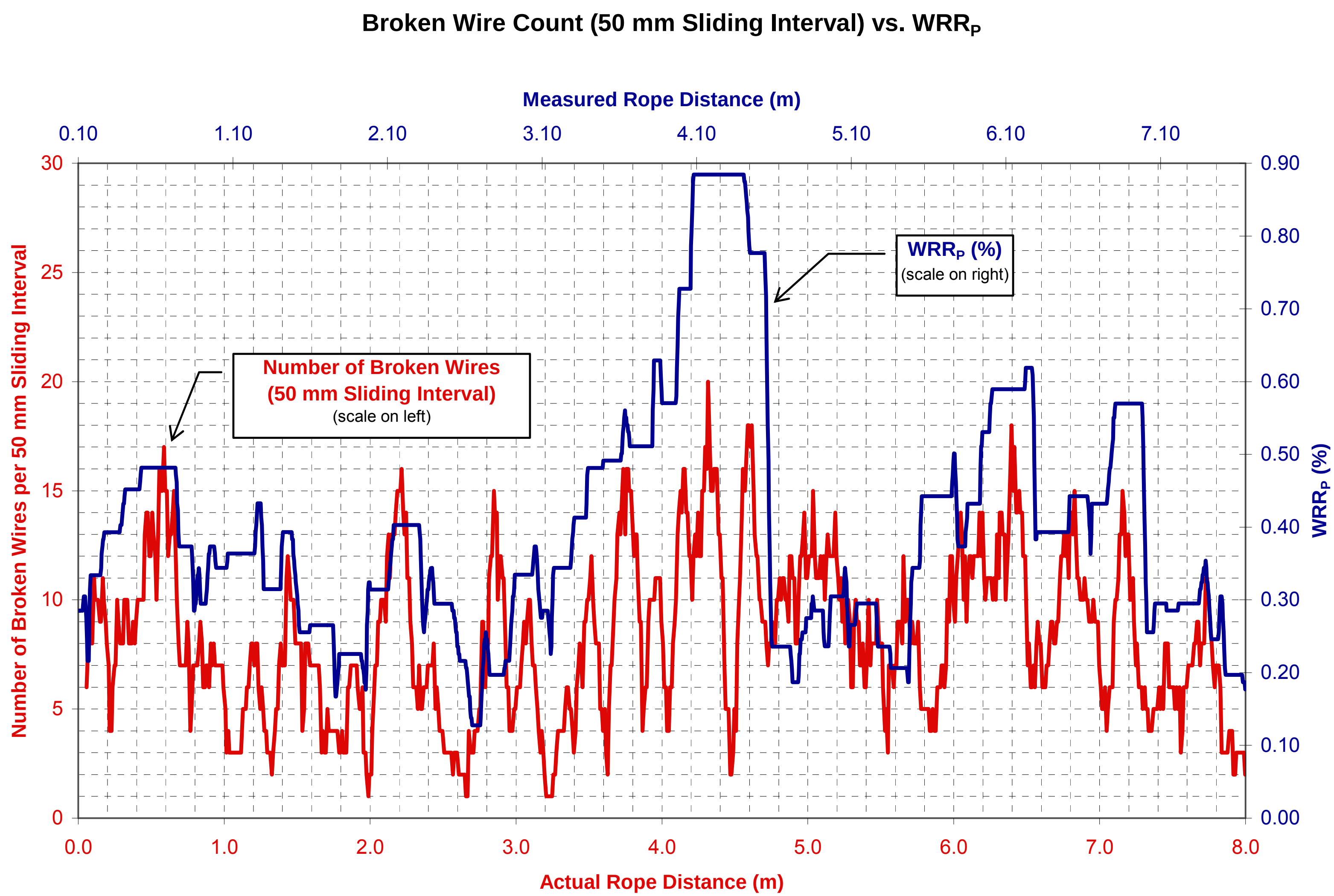


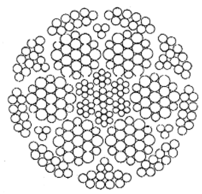
FIGURE 12. Rope 1, comparison of broken wire count vs. WRR_P (distance adjusted)



Test 2: [6]

This test concerns a 36 mm diameter, 21 strand – 21 (9 x 6 x 6) construction, multilayer, low rotation rope (Figure 13). The rope will be referred to as Rope 2 in the following.

FIGURE 13. Multi-strand rope construction



36 mmΦ / 21 Strand / Non-Spin / IWRC Multistrand Rope

Rope 2 was in very good condition except for an approximately 3 m length exhibiting heavy corrosion.

Figure 14 shows an inspection chart recording of this rope. The chart is used to show the inspection results before and after *signal enhancement*. As mentioned above, the so-called *Echo Effect* convolutes the LMA signal. However, the signal can be de-convoluted by the above mentioned *echo cancellation* or *signal enhancement* algorithm.

To facilitate a side-by-side comparison of the LMA signal before and after enhancement, the two traces are overlaid. Note that, compared to the acquired signal, the enhanced signal has noticeably better resolution. In other words, the enhanced signal reveals more details of the rope condition.

This is important for the following WRR Analysis that relies on a high-resolution signal in order to make the rope inspection accurate and reliable. Furthermore, the maximum LMA values indicated by the enhanced signal are slightly higher and more accurate than those of the unprocessed signal.

Figure 15 shows the WRR Analysis of Rope 2. Both traces of the chart show severe corrosion. Here, the LMA signal indicates an 18% cross-section loss, while the WRR trace indicates a wire rope roughness of over 3%. By all accepted retirement criteria, this degree of deterioration warrants discard of Rope 2.

FIGURE 14. Rope 2, LMA signal before and after echo cancellation

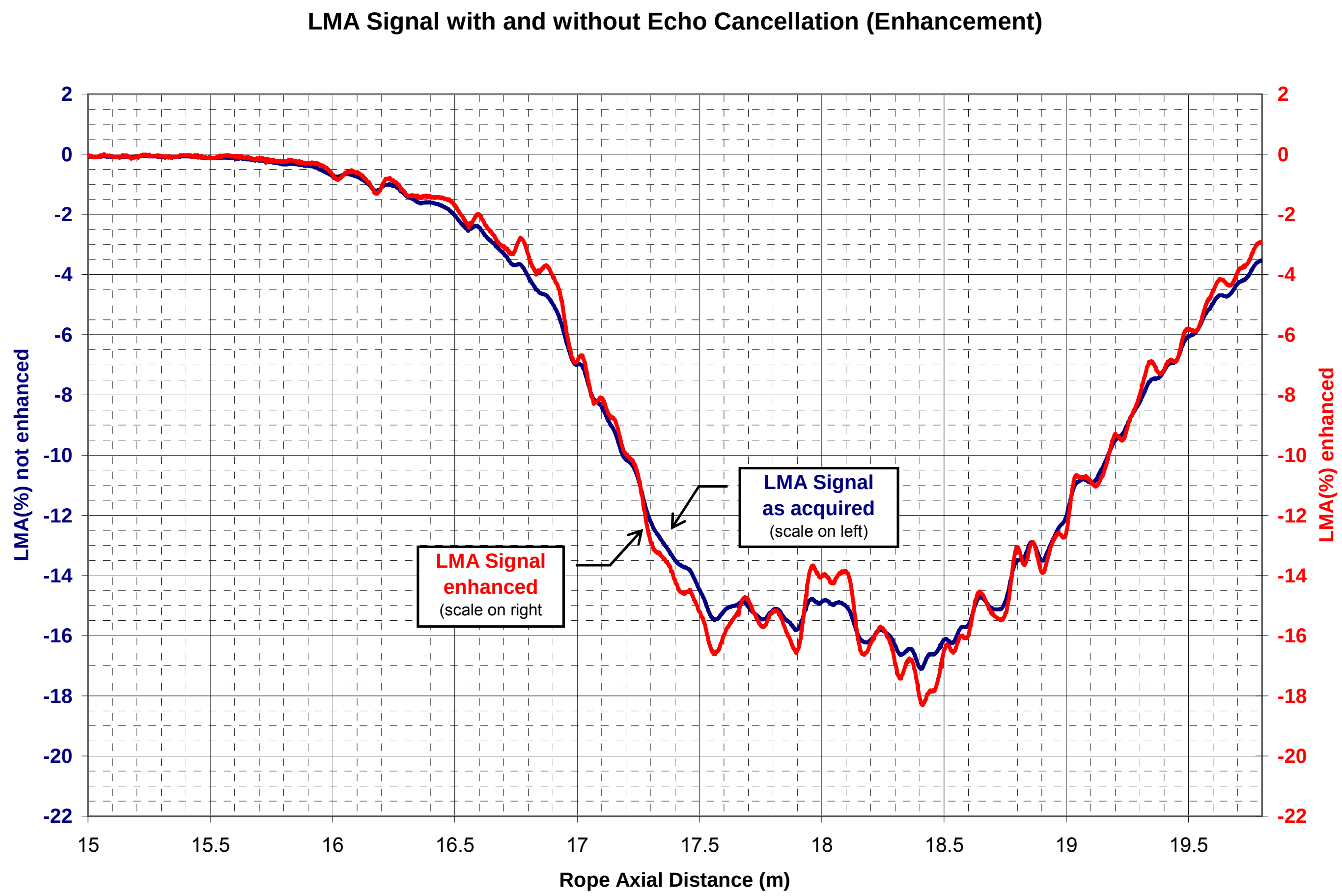
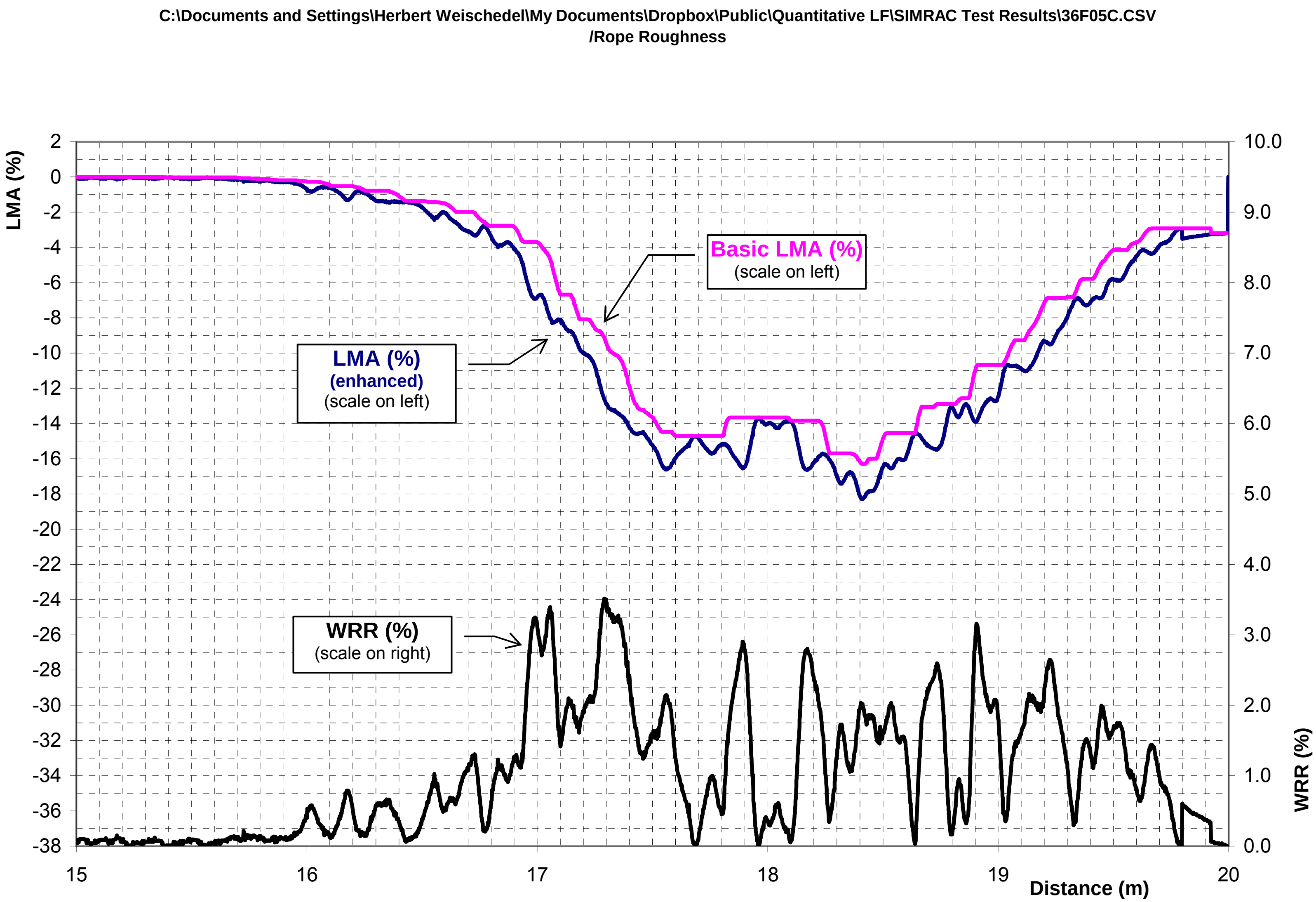


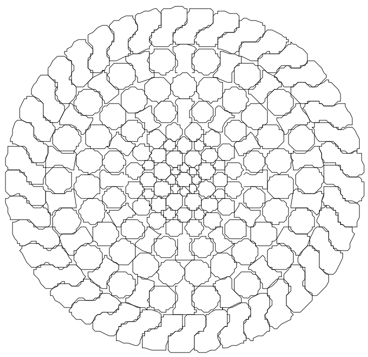
FIGURE 15. WRR Analysis of Rope 2



Test 3: [7]

For this test, a 32 mm locked coil rope, left hand lay rope was used. Figure 16 shows its construction.

FIGURE 16.
Locked Coil rope construction



This locked coil rope was mounted on a mobile winch for approximately 10 years after 3 months earlier use on a friction winder installation. Its cross-sectional diagram is shown in Figure 16. The rope showed clear evidence of external corrosion, variable along the test length. Using retirement criteria that are appropriate for visual inspections, this rope would have been rejected for further use. Due to its service history the rope was not believed to contain any internal broken wires.

Examination after dismantling. After dismantling, the rope showed severe corrosion on the outer layer and also significant corrosion on the second layer. The third layer showed less corrosion, and from the fourth layer onward the rope appeared undamaged, because lubricants were still present. No broken wires were found (see Figures 17 and 18).

Figure 17. Corrosion in the first and second layer of the rope

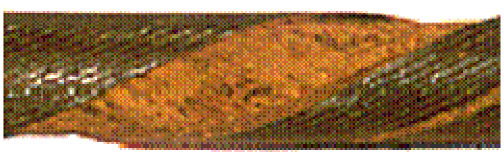
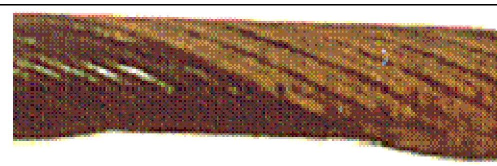


Figure 18. Corrosion in the second and third layer of the rope



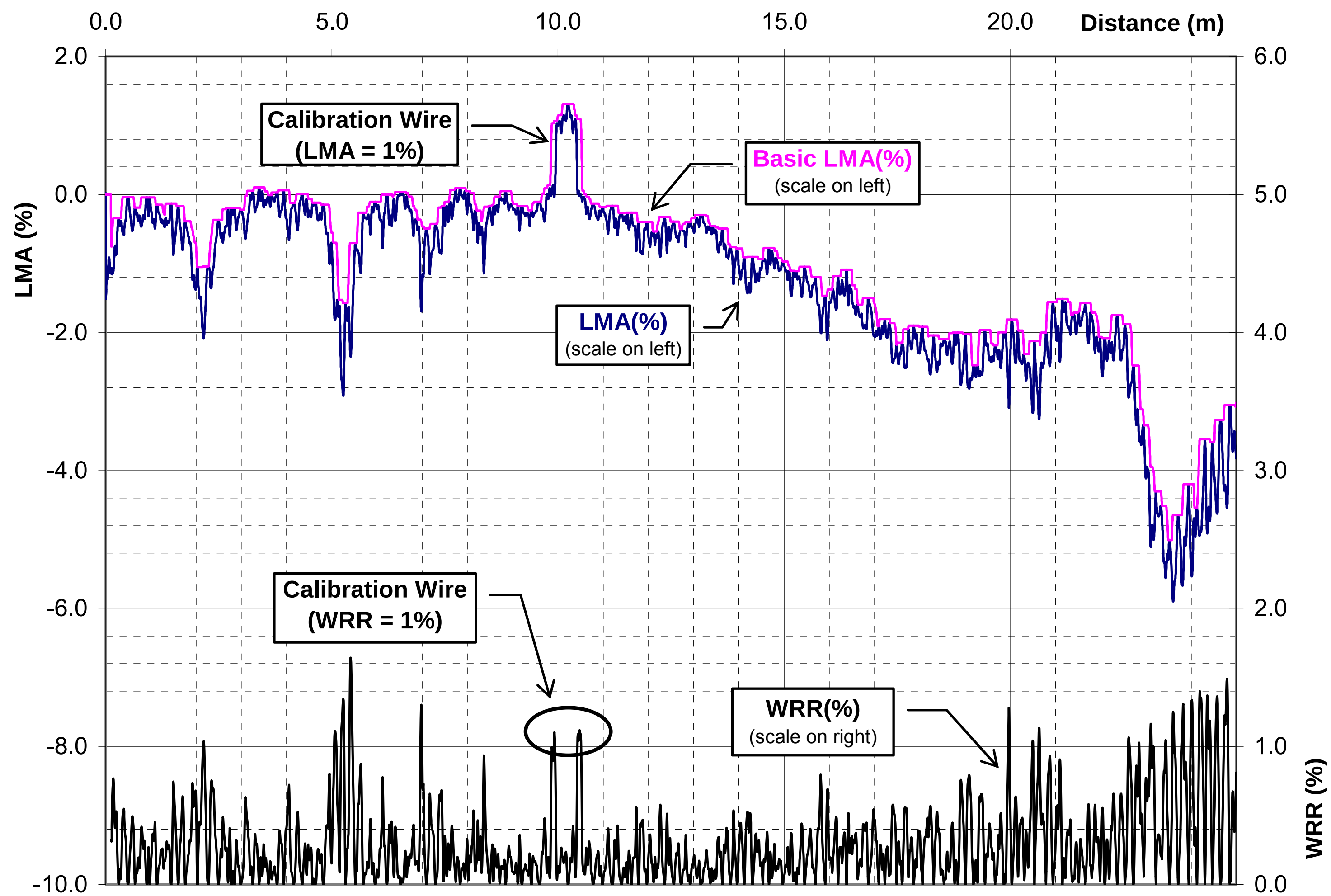
Findings of electromagnetic inspection. Figure 19 shows an inspection chart, including WRR Analysis, of this rope. The maximum measured LMA is almost 6% compared to the best section on the rope covered by the chart.

The deterioration pattern indicated to the left of the chart is typical for ropes that wind on a drum with the worst deterioration occurring at the crossover points as the rope slips from layer to layer while winding on a multilayer drum.

Note that the most convenient calibration method for EM inspections is to attach a calibration wire with known cross-sectional area to the rope. In the present case, a wire bundle that represents about a 1% increase in rope cross-section was taped to the rope and used for calibration. This is indicated in the chart.

The WRR signal is extracted from the LMA signal, and the WRR Analysis method is designed in such a way that the LMA as well as the WRR signal are calibrated simultaneously. This feature is illustrated by Figure 18. It shows that, while the calibration wire bundle represents a 1% increase of cross-sectional area, both ends of the wire bundle show a corresponding 1% WRR as indicated in the chart.

FIGURE 19. WRR Analysis of Rope 3



Rope 3 shows a maximum LMA of about 6%. This is less than the typical 10% LMA limit that is frequently used as a retirement condition. On the other hand, retirement based on a visual inspection after rope destranding was well justified.

The chart recording in Figure 19 shows a maximum WRR of about 1.6% at a rope distance of 5.4 m. This result, together with the previous tests, suggests that a WRR value of 1% - 2% could be used as a retirement criterion for a rope that shows signs of corrosion pitting and/or internal broken wire clusters.

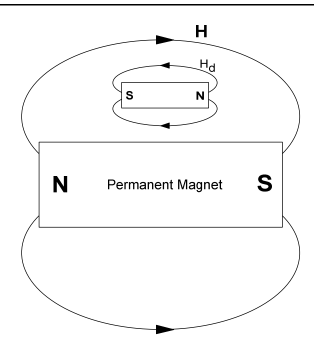
EFFECT OF MAGNETIC DEBRIS ON THE ACCURACY OF LMA MEASUREMENTS

Rope deterioration of the WRR type usually produces wear and/or corrosion debris in the form of a fine powder trapped inside the wire rope. Since these deterioration products are usually ferromagnetic, they will cause an additional magnetic field in the cable, thus contributing to the magnetic flux. Conceivably, this additional flux could result in an overestimation of the true load-bearing metallic cross-sectional area, and hence an underestimation of the LMA and WRR of a cable.

However, a closer look at this situation shows that trapped magnetic debris only marginally affects the quantitative evaluation of LMA (and WRR).

A strong magnetic field can easily magnetize an elongated body of sufficient length, such as a wire rope, to the saturation level. For a short object, however, magnetic saturation is not as easy to achieve. This is due to the demagnetization effect. Magnetization of a ferromagnetic body of finite length produces free magnetic poles on the surface, where the normal component of the magnetization changes. This can be visualized by considering the following example.

Figure 20. Demagnetization



Consider the magnetic field **H** of a permanent magnet shown in Figure 20. If a ferromagnetic object is inserted into the field **H**, the object becomes magnetized and the field intensity, H, at the surface of the metal object is reduced from the value it was in the air.

In the magnetization process, the left-hand end of the metal object becomes an **S**-Pole and the right-hand end becomes an **N**-Pole. These poles create a – so-called – demagnetizing field $\mathbf{H_d}$, which opposes the field **H** from the permanent magnet. Hence, the effective field acting on the metallic body is always less than the applied field **H**. Since $\mathbf{H_d}$ is inversely proportional to the distance between poles (or the length of the object), it can become substantial for short objects. The net effect is that, to obtain the same flux density **B** in the metal object as if it has no free poles, one has to raise the applied field **H** by an amount equal to the demagnetizing field.

For short ferromagnetic objects, McClurg [8] has shown that the apparent relative permeability μ_{app} (defined as B/H) of an elongated object can be approximated by the formula

$$\mu_{app} = 6(L/D) - 5$$

Where L is the length and D is the diameter of the object.

Thus for a short cylinder with an L/D ratio of 1 (or a sphere), the McClurg formula indicates an apparent relative permeability value close to 1, which is that of air. This is considerably lower than values such as 400 – 1000, which might be obtained if experiments were performed on ring samples of the same material. This means, for a spherical iron specimen, the applied field must exceed 4,000 – 10,000 Oersted in order to bring it into saturation, while an infinitely long elongated steel object would require only 10 Oersted.

According to the above discussion, it can be assumed that the apparent relative permeability of loose powder – that is made up of fine particles trapped inside a cable – is close to 1, or that of air. This is so because each particle can be considered a spherical specimen. This assumption is valid if each particle is not in direct physical contact with the rest of the ferromagnetic body. Also, it is a fair assumption that, while the magnetic field produced by the EM tester is strong enough to saturate a length of wire rope, it is not strong enough to appreciably magnetize the trapped debris. It follows that the total magnetic flux in the magnetic circuit – and hence the LMA reading of the EM instrument – is not significantly affected by the debris trapped inside the cable.

Experiments confirm the above considerations [9].

SUMMARY AND CONCLUSION

Methods for nondestructively assessing and characterizing wire rope degradation that is caused by internal corrosion pitting and clusters of broken wires have not been available in the past.

This paper introduces a new concept called *Wire Rope Roughness (WRR)* that is defined as the surface roughness of the aggregate wires of a rope. For individual wires, roughness is defined as the high (spatial) frequency, short (spatial) wavelength component of wire surface variations.

A new method for determining WRR by extracting a WRR signal from the Loss of Metallic Cross-Sectional Area (LMA) signal is presented.

Extraction of a high-quality WRR signal calls for a high-fidelity LMA signal with excellent resolution to start out with. This signal must record accurately even small-scale high-frequency features on the aggregate wire surfaces. This requirement rules out any filtering, low-pass or other, which is frequently used to improve signal-to-noise ratios.

Furthermore, it is desirable to remove from the LMA signal, as much as possible, artifacts that are introduced by the sensor head geometry. One such elimination method is described.

The new WRR characterization approach was applied to several wire rope samples with well documented deterioration features – such as internal corrosion pitting and internal broken wires in clusters. Correlation between the WRR signal and the actual conditions of the test ropes is excellent, which proves the feasibility and effectiveness of the new WRR Analysis method.

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