

The Electromagnetic (EM) Inspection of Offshore Wire Ropes

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Introduction

Because the reliable and safe use of wire rope is crucial for offshore applications, concern with their integrity is a constant preoccupation of wire rope operators and safety authorities. In spite of these concerns, a reluctance to apply appropriate inspection methods and discard criteria compromises the safety of many offshore operations. A recent multi-hundred-million-dollar accident, caused by a wire rope failure, underscores the importance of reliable wire rope inspection methods.

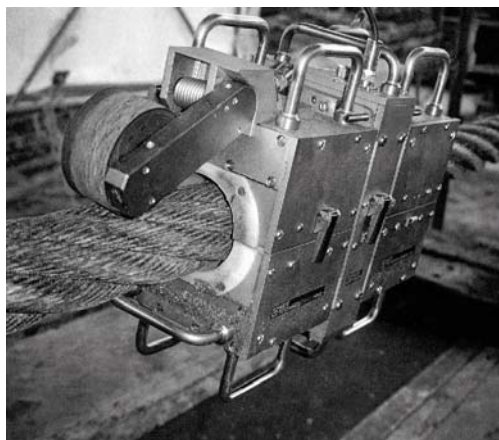
Because many offshore ropes deteriorate internally without externally visible signs, their inspection solely by visual methods is unsafe. In other cases, visual inspection is possible but not practical. For example, mooring ropes are often covered with mud and marine growth. This makes their visual inspection difficult, if not impossible.

When visual inspections are impossible, rope operators usually resort to a *statutory life* policy as an alternative. (The *statutory life* method requires rope retirement at prescribed, fixed intervals.) By definition, this approach must be extremely conservative and, therefore, wasteful. For example, presently, countless perfectly good crane ropes - worth many millions of dollars - are discarded at regular annual intervals. And yet, in spite of this very uneconomical practice, occasional rope failures still occur.

More dependable inspection methods, combined with a better understanding of degradation mechanisms and discard criteria, can notably increase wire rope safety. For example, electromagnetic (EM) nondestructive inspections at regular intervals can significantly increase the safety of offshore ropes. EM inspections are particularly effective when they are combined with visual examinations and a thorough understanding of rope deterioration modes.

Two different and distinct EM methods have evolved for the detection and measurement of rope defects

- *Loss of Metallic Cross-Sectional Area (LMA) Inspection*, which (quantitatively) measures loss of metallic cross-sectional area caused by external or internal corrosion (due to environmental conditions or poor lubrication) and wear (due to rubbing along floors, nicking, high pressures, and/or poor lubrication).
- *Localized-Flaw (LF) Inspection*, which (qualitatively) detects a wide variety of external and internal discontinuities such as broken wires and corrosion pitting. Broken wires are usually caused by fatigue, interstrand nicking and martensitic embrittlement.



Modern dual-function EM rope testers allow simultaneous LMA and LF inspections. Figure 1 shows the EM inspection of an oil platform mooring rope.

Underlying Principles

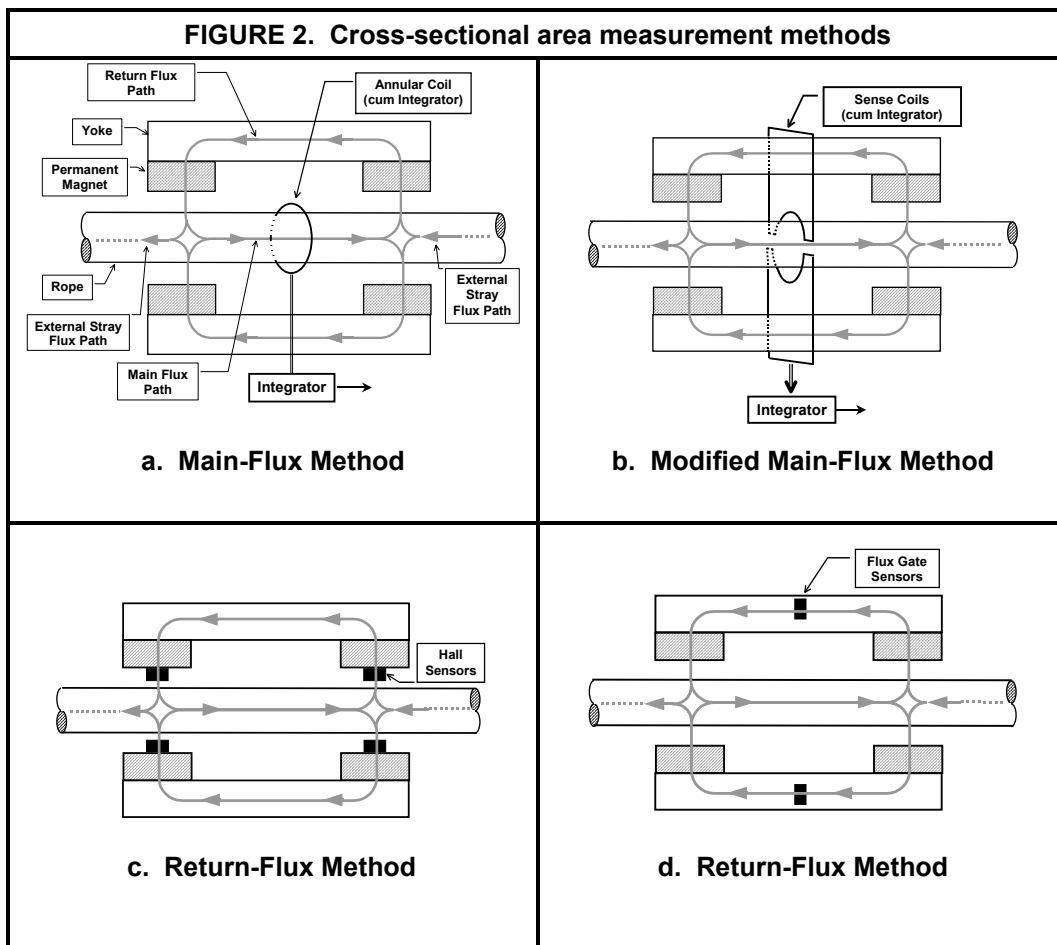
For all present dual-function instruments, strong permanent magnets induce a magnetic flux at the saturation level in the rope in the axial (longitudinal) direction. Various types of sensors, such as coils, Hall sensors or fluxgate sensors close to the rope sense and measure the magnetic flux.

Any discontinuity – such as a broken wire or corrosion pitting – distorts the magnetic flux in the rope and causes it to leak from the rope. For LF inspections, the *radial* component of the leakage flux is measured by so-called *radial* sensors. Note that these sensors are also called *differential* sensors because they sense only changes of the magnetic flux in the rope and not the flux itself. Therefore, flaw detection depends on a rapid change of the magnetic flux, which is typically caused by broken wires and corrosion pitting. Differential sensors cannot detect more gradual changes of the rope flux, which are typically caused by wear and corrosion.

Methods for the (quantitative) measurement of the LMA of a rope are discussed in the following. When a rope is magnetically saturated, the axial magnetic flux in the rope is proportional to its cross-sectional area. Therefore, any LMA can be determined by measuring this magnetic flux. Two types of sensors can be used to measure magnetic flux: Hall sensors (or, alternatively, fluxgate sensors) and coils in combination with electronic integrator circuits.

To measure flux density, Hall sensors (and fluxgate sensors) must be physically inserted directly into the magnetic flux path. Thus, the flux to be measured must intersect the sensors. This is not possible when measuring the magnetic flux inside the rope. Therefore, instruments that use Hall sensors or fluxgate sensors must always resort to an indirect method for determining the axial rope flux. They measure some flux density outside the rope and determine or estimate the longitudinal rope flux from the external flux measurement. Alternatively coils-cum-integrators can be used. Because coils must encircle the magnetic flux to be measured, they can directly measure the magnetic flux inside the rope. Currently, two generic methods are used for the determination of LMA. They are illustrated in Figure 2.

The **Main-Flux Method** uses an annular coil together with an electronic integrator circuit to determine the local magnetic flux inside the rope (Figure 2a). Note that the coil must encircle the rope. Originally patented¹ in Britain in the 1960s, this approach has been discussed in the literature.^{2, 3, 4} Since it measures the magnetic flux inside the rope locally, the annular coil approach offers uncommon resolving power, signal fidelity and, therefore, inspection accuracy. The performance of this arrangement is unsurpassed and must be considered the *Gold Standard* by which all other methods are measured.



Unfortunately, it is topologically impossible to implement a hinged annular coil with a large number of turns that can be opened and conveniently attached to the rope. This means, the practical implementation of the main-flux method for in-service wire rope inspections is seriously hampered by an inherent and insurmountable problem: An annular coil – encircling the rope – must be wound onto the rope in the field for each inspection. This

cumbersome procedure allows only very few turns (say, one hundred) and, hence, only very small induced coil voltages. The coil voltages are of the same order of magnitude as the always-present offset voltages at the input of operational amplifiers that are used for the design of electronic integrator circuits. These inherent offset voltages make the long-term low-drift integration of the coil voltages impossible. Hence, the annular coil approach is not feasible for in-service inspections where LMA measurements over longer time periods – say, over more than a few minutes – are required.

The **Modified Main-Flux Method**, shown in Figure 2b, tries to retain the superior performance of the *Main-Flux Method* while allowing the implementation of hinged sense heads of the *clamshell* design.^{3,4}

The test signals of this *Modified Main-Flux Method* are a combination of the *Main-Flux* signal and a signal component that is caused by the (parasitic) *outside stray flux*, i.e., that portion of the flux that leaves and enters the sense head to and from the outside, respectively, and flows along some external stray flux path (see Figure 2). Unfortunately, this *outside signal component* is significant. It compromises the quality of the test results and must be considered parasitic. Although this parasitic effect can be minimized,⁵ a true signal of the *main flux* type cannot be completely restored. Nevertheless, the *Modified Main-Flux Method* retains at least some of the desirable features of the *annular coil* approach.

The **Return Flux Method** uses Hall sensors^{6,7} (or, more complex, fluxgate sensors⁸) to measure the magnetic flux in the magnetic return path of the instrument. Illustrated by Figures 2c and d, the return flux is equal to the *average value of the axial rope flux* inside the sense head plus the *outside stray flux*. Therefore, the return flux provides an estimate of the *average cross sectional area* of that section of the rope that is inside the sense head. Flux sensors can either be inserted into the air gap between the permanent magnet poles and the rope or into the yoke of the magnetizer assembly. The return-flux method allows the design of hinged sensor heads of the *clamshell* type. This feature makes it possible to attach the sensor head to the rope even under adverse field conditions.

Signal Generation and Evaluation⁵

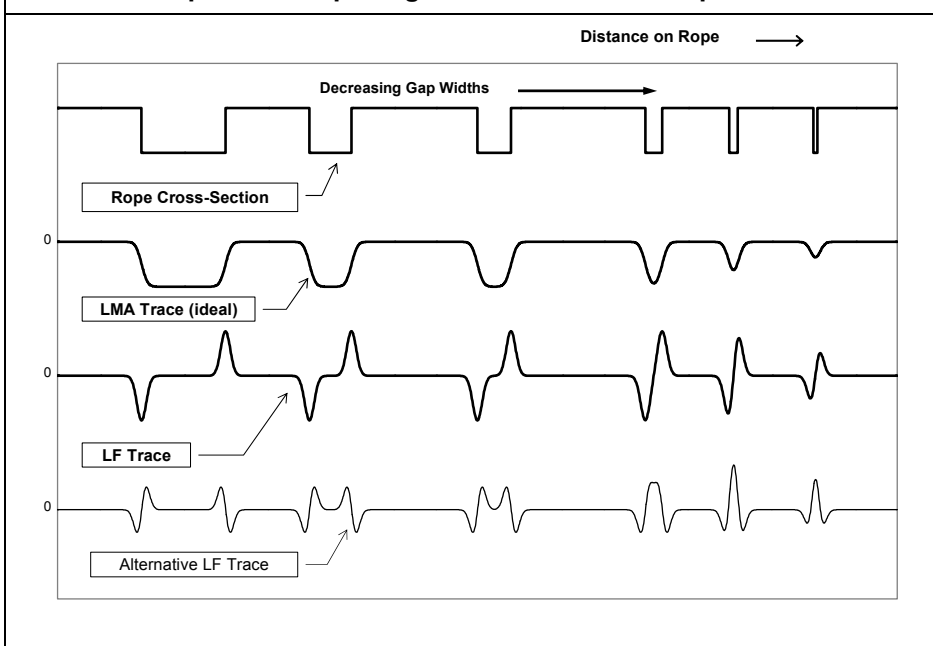
For the interpretation of test results and for a correlation of test data with the actual rope condition, the rope inspector must understand the capabilities and limitations of his EM rope inspection equipment. A proper appreciation of the signal generation process, together with an understanding of rope degradation mechanisms and discard criteria, is essential for making rational rope retirement decisions.

For the following discussion, *step changes of metallic cross-sectional area* – caused by missing or added wires, for example – have particular significance. Because of its simple geometry, a *step change* can be called a *fundamental defect*. Accordingly, the corresponding LMA and LF signals, caused by a *fundamental defect*, can

be called *fundamental LMA* or *LF signals*, respectively. The *fundamental signals* can also be called an instrument's *step response*.

It is easy to see that any defect can be represented as the sum of appropriately scaled and spaced *fundamental defects*. Moreover, the process of signal generation is, at least approximately, linear. Hence *linear superposition* applies. This means that, if a defect can be represented as the sum of several *fundamental defects*, then the corresponding defect (LMA and LF) signals are the sum of the corresponding *fundamental LMA* and *LF signals*. The concepts of *fundamental defects* and *signals*, *step response*, and *linear*

FIGURE 3. Input and output signals of an idealized rope test instrument



superposition are discussed further in the literature.⁹ Determining and evaluating its *step response* is an excellent method for characterizing the performance of an EM wire rope tester.

In the present context, the concept of filtering can be used very loosely. For example, the sensor head of an EM rope tester, together with the signal electronics, may be viewed as a – linear or nonlinear – data filter. This is illustrated further by Figure 3. The figure depicts the rope cross-section as the input signal and the idealized corresponding LMA and LF output signals. Note that, for many rope testers, the LF signal approximates the first derivative of the rope cross-section signal. For other instruments, the LF signal is the second derivative of the rope cross-section, as shown as *Alternative LF Signal* in Figure 3. Note that the signals generated with the *Main Flux Method*, shown in Figure 2a, closely resemble the idealized results of Figure 3.

Recognizing differentiation as the quintessential high-pass filter operation, the LF signal can be considered as the rope cross-section input signal that has been high-pass filtered. High-pass filtering accentuates fast changes of signals, and, typically, broken wires and corrosion pitting cause rapid variations of the rope cross-section. Therefore, the high-pass filtering feature makes the *LF Signal* useful for the detection of broken wires and corrosion pitting.

Any inspection equipment should present data in a form that facilitates their interpretation by the human operator. Figure 3 shows that a perfect LMA signal could serve as such an accurate and conceptually simple map of a rope's LMA that is easy to interpret by the inspector.

Resolution and Averaging Length

The dictionary defines *resolution* as “the level of detail that can be distinguished in an image (or a recording).” For electromagnetic wire rope inspections, resolution is always the premier performance measure. In nondestructive testing, the terms *resolution* and *inspection accuracy* are often used synonymously. In the discipline of electromagnetic wire rope inspection, *quantitative resolution*³ 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 a rope's LMA.

To visualize the concept of *averaging length*, assume that, instead of measuring metallic cross-sectional area directly, the rope tester continuously measures the metallic volume of consecutive rope sections with lengths that are equal to its *averaging length*. Figure 4 illustrates this concept.

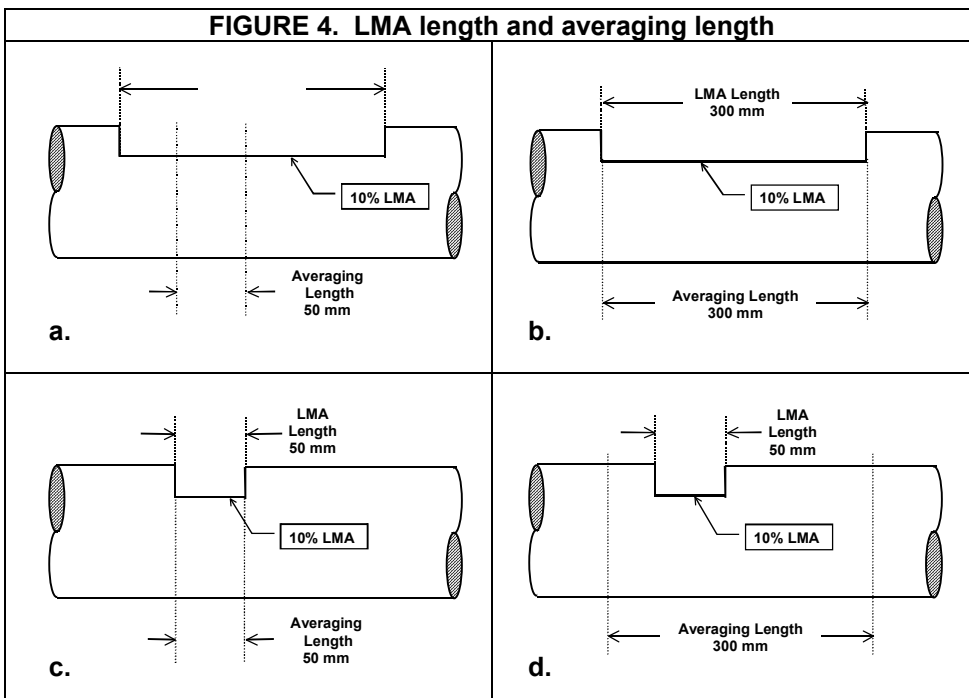
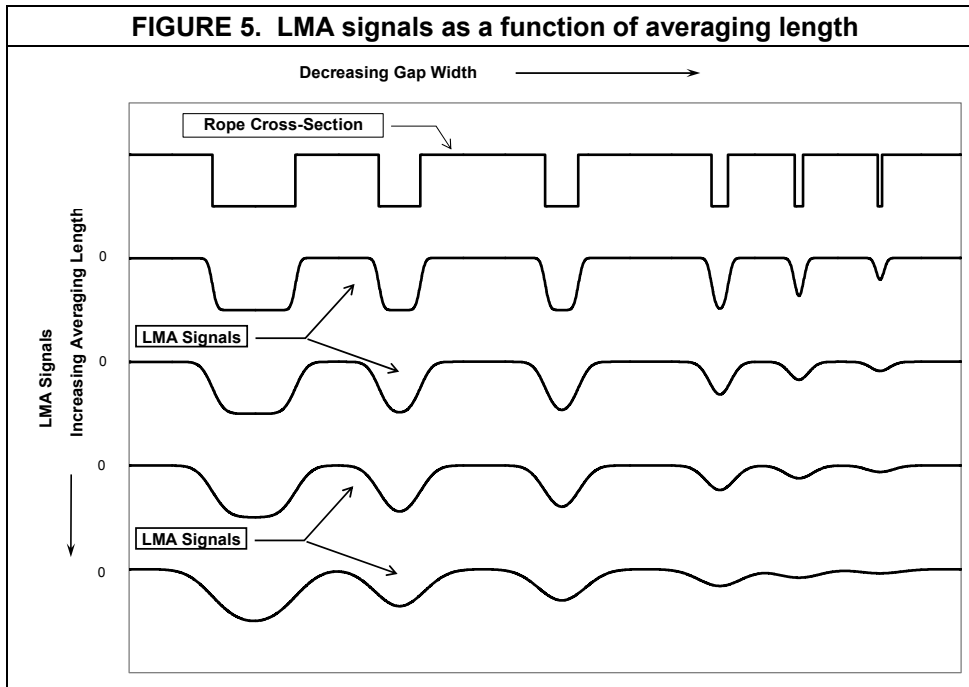


Figure 4a shows a (hypothetical) rope with a uniform 10% LMA extending over a length of 300 mm. An instrument with a 50 mm *averaging length* will correctly measure this LMA. As illustrated by Figure 4b, a rope tester with an *averaging length* of 300 mm will also give a true indication of this anomaly.

Now consider a (hypothetical) rope with a 10% uniform LMA extending over a length of 50 mm. Figure 4c shows that an instrument with an *averaging length* of 50 mm can determine the exact LMA caused by this anomaly. However, as can be seen from Figure 4d, an instrument with an *averaging length* of 300 mm would indicate the

same anomaly as a 1.7% LMA extending over a length of 300 mm – a very inaccurate indication of the true rope condition. These examples show the importance of a short *averaging length*.

FIGURE 5. LMA signals as a function of averaging length



Note that signal averaging is a quintessential type of low-pass filtering, and that signals lose a significant amount of information (details) by low-pass filtering. Figure 5 illustrates this situation. It shows how the quality of LMA signals deteriorates as the averaging length increases.

An analogy can illustrate the problems associated with long LMA averaging lengths: A chain is only as strong as its weakest link. Obviously, the strength of a chain is not determined by the average strength of some of its links. Similarly, the

strength of a rope, which has lost metallic cross-section by corrosion and/or wear, is determined by the minimum local metallic cross-sectional area along the rope's length, and not by some average value of the rope cross-sectional area.

Experience has shown that serious rope deterioration can occur over very short distances along the length of a rope. Hence, in order to determine and evaluate a rope's actual metal loss with acceptable accuracy, a short *averaging length* – of no more than a few centimeters – is important.

Because all wire rope testers have a *quantitative resolution* or *averaging length* that is greater than zero, an accurate measurement of LMA always requires minimum lengths of anomalies. As the above discussion shows and as illustrated by Figure 5, the concept of *quantitative resolution* or *averaging length* is important for specifying and comparing the performance of rope testers.

Wire Rope Inspection and Retirement

Two different philosophies have been used to effect rope retirement:

1. A *Statutory Life Policy* mandates rope retirement at certain prescribed intervals.
2. *Retirement for Cause* is based on retirement conditions that are evaluated periodically by nondestructive inspections.

Because a *Statutory Life Policy* is inherently wasteful, regulators have tended to adopt the *Retirement-for-Cause* approach wherever appropriate.

Wire rope deteriorates gradually throughout its entire service life. To keep abreast of deterioration, wire rope must be periodically inspected. Because moderate deterioration is normally present, the mere detection of rope deterioration does not usually justify rope retirement. There are two major nondestructive inspection methods for the detection and evaluation of rope degradation: Visual inspections and EM inspections.

Visual Inspection

Visual inspections are a simple yet useful method for detecting a wide variety of external rope deteriorations. Using this approach, the rope is moved two or three feet at a time and visually examined for broken wires and other rope deterioration at each stop. This method is tedious and, because the rope is often covered with grease, many external and internal defects elude detection.

Another visual inspection tool is measurement of the rope diameter. Rope diameter measurements compare the original diameter – when new and subjected to a known load – with the current reading under like circumstances. A change in rope diameter indicates external and/or internal rope damage. Inevitably, many sorts of damage do not cause a change of rope diameter.

Visual inspections are inherently not well suited for the detection of internal rope deterioration. Therefore, they have limited value as a sole means of wire rope inspection. However, visual inspections are simple and do not require special instrumentation. When combined with the knowledge of an experienced rope examiner, visual inspection can provide a valuable supplementary tool for evaluating many forms of rope degradation.

Electromagnetic Inspections

As discussed, EM wire rope inspection gives detailed insight into the condition of a rope. Its reliability has made EM testing a universally accepted method for the inspection of wire ropes in mining, for ski lifts, and many other applications.

Combined Inspections

Electromagnetic and visual wire rope inspections complement each other. Both are essential for safe rope operation, and both methods should therefore be used for maximum safety.

A thorough inspection must consider all aspects of a rope's condition, including:

1. The findings of a visual inspection,
2. the results of an EM rope inspection,
3. the rope's operating conditions and related damage mechanisms,
4. the history of the rope under test and that of its predecessors.


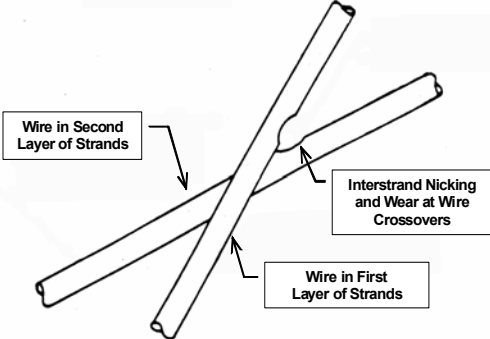

Dependable inspection procedures, using combined visual and EM methods, can detect rope deterioration at its earliest stages. Therefore, wire rope users can employ them as an effective preventive maintenance tool. To illustrate, here are some practical examples.

1. The early detection of corrosion allows immediate corrective action through improved lubrication.
2. Accelerating wear and interstrand nicking can indicate a need to reline sheaves to stop further degradation
3. Careful inspections can monitor the development of local damage at the crossover points of the rope on a winch drum. This way, the operator can determine the optimum time for repositioning the rope on the drum.

A program of periodic inspections is especially effective. To establish baseline data for subsequent inspections, such a program should commence with an initial inspection of the installed rope after a certain break-in period. Subsequent inspections should then be performed at scheduled intervals. In particular, periodic EM inspections allow the documentation of a rope's deterioration over its entire service life.

Offshore Ropes^{10, 11}

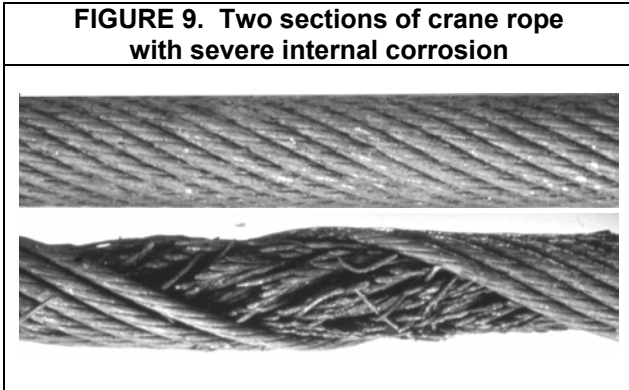
Many offshore crane and diving bell ropes are of the torque-balanced multistrand type comprising two or more layers of strands. Figure 6 shows a cutaway section of such a multistrand rope. Torque balance is achieved by laying outer and inner strands in opposite directions. This type of rope construction limits axial rotation of the freely suspended rope under load. In addition, multistrand ropes offer flexibility and a wear resistant surface profile.

FIGURE 6. Multistrand Rope construction	FIGURE 7. Interstrand nicking	FIGURE 8. Broken wires in second layer of strands
		

However, the wires and strands in different layers of these ropes touch locally and at an angle. Therefore, when multistrand 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. This causes fretting wear or fatigue and interwire nicking across the interface between layers as illustrated by Figure 7.

Therefore, multistrand ropes are prone to develop internal broken wires. This breakup occurs primarily on the interface between the outer and second layer of strands, usually with no externally visible signs (see Figure 8). The wires in the second layer of strands typically show interstrand 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.



Many multistrand 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 where there is no effective form of protection. The combined effects of fatigue, corrosion, and lubricant degradation can cause fairly rapid internal degradation with no externally visible indications. Figure 9 illustrates this situation. The upper part of the figure shows the external appearance of an offshore crane rope; the lower part is another section of same rope with the outer strands stripped away. While it

would be straightforward to detect this type of rope deterioration with an EM inspection, this situation is by no means unique and has caused several in-service rope failures.

Example 1. Diving bell rope inspection.

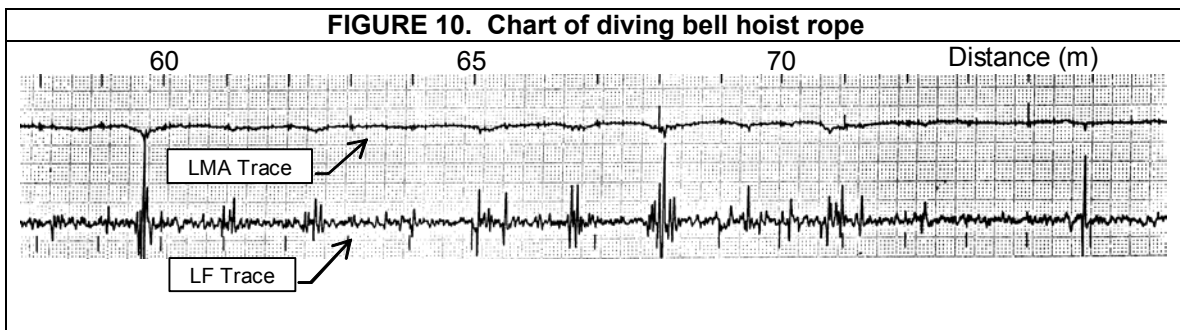


Figure 10 shows an EM inspection chart recording of a 30 mm die-formed multistrand diving bell hoist rope. The rope shows periodic groups of broken wires, probably at cross-over points on the winch drum. The maximum LMA is 1%. The external broken wires could be identified visually. This rope section is subjected to the full in-air weight as the bell is lowered and raised. On the basis of the EM inspection, a decision was made to cut and reterminate the rope behind the first defect about 58 m from the diving bell.

Example 2. Experimental multistrand rope inspection

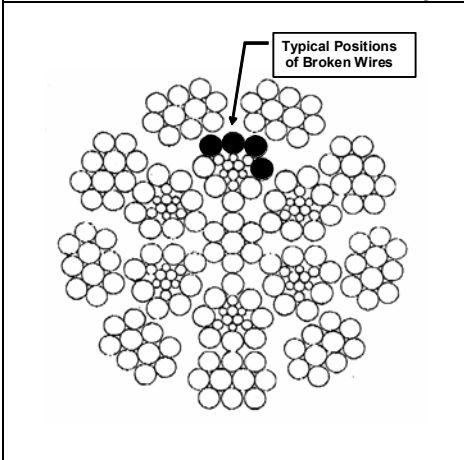
This case study illustrates the use of EM wire rope inspections for the detection and quantitative characterization of internal broken wires and clusters of broken wires in multistrand ropes. The present experiment deals with the inspection of a torque balanced multistrand rope with no corrosion and many internal broken wires. This rope has been used on a trial basis and was known to contain numerous internal broken wires along its entire length.

The task at hand was to determine the number of broken wires in 100 mm segments along the length of the rope. The difficulty of this quantitative defect characterization problem was compounded by the fact that an undamaged rope section was not available for comparison. Further, at the time, the correlation of the typical deterioration modes of this and similar ropes with their EM inspection results was generally not well understood.

A cross-sectional diagram of this multistrand rope is shown in Figure 11. As indicated in the figure, it is known that broken wires in multistrand ropes usually develop in the second layer at the interface between the first and

the second layer of strands. In addition, from this and similar ropes' service histories, it can be assumed that the rope under inspection has developed significant interstrand nicking together with numerous fatigue breaks of wires in the second layer of strands.

FIGURE 11. Typical position of broken wires in a multistrand rope

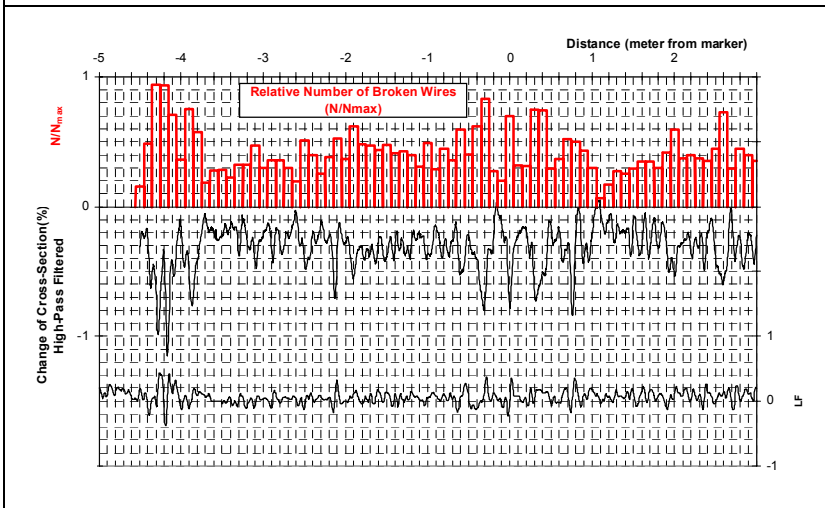


The detailed detection and quantitative characterization of internal broken wires in ropes with many breaks and clusters of breaks – such as the present rope – pose problems. Difficulties are caused by the fact that, for electromagnetic wire rope inspections, the indication of a broken wire is influenced by a number of parameters like

- broken wire cross-sectional area,
- broken wire gap width, and
- by the position of the broken wire within the cross-section of the rope.
- 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.
- 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.

FIGURE 12. LMA and LF traces and relative number of broken wires



Conventionally, the LF trace is used for the detection of broken wires. However, the LF signal is not quantitative and can not be used for estimating the number of broken wires. On the other hand, the LMA trace of the inspection chart in Figure 12 shows rapid relatively small variations of cross-section. These variations are significant and can be used to estimate the number of broken wires per unit of rope length. Note, however, that the *averaging length* or *quantitative resolution* of the instrumentation used must be sufficient to allow this quantitative defect characterization.

The estimated number of broken wires per 100 mm of rope length, N , derived from the LMA trace, is shown on the top of Chart 12. Here, N_{max} denotes the maximum number of broken wires per

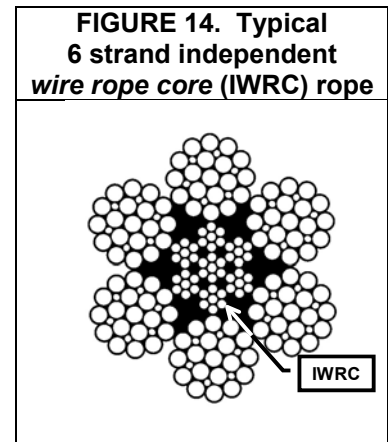
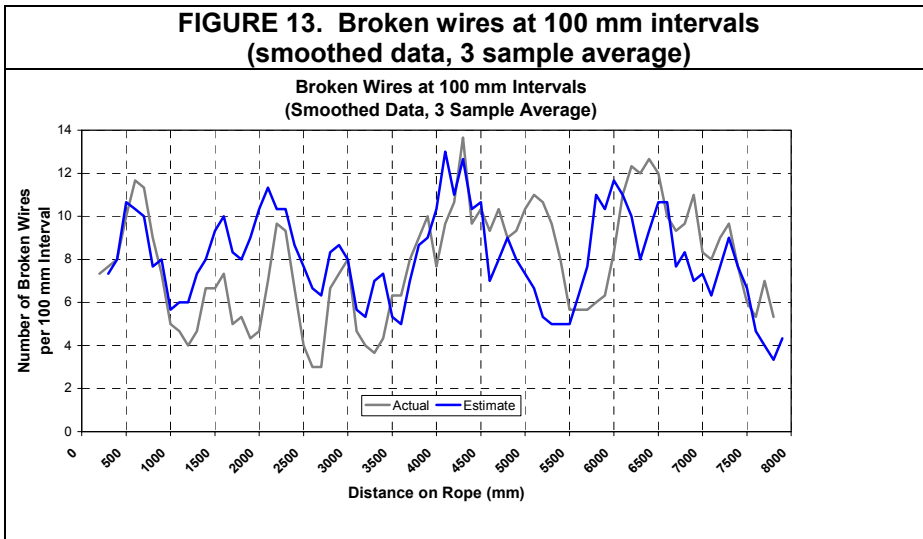
100 mm of rope length. Based on the operating history of this and similar ropes, a value of $N_{max} = 20$ can be estimated.

The rope was subsequently disassembled¹² to determine the actual number of broken wires per unit of rope length. Broken wire estimates together with the actual number of broken wires along the length of the rope are shown in Figure 13. Considering the fact that the LMA trace not only indicates broken wires but also interstrand nicking, internal wear and other disturbances of the rope structure, there is a good correlation between the actual and estimated number of internal broken wires. The correlation between actual and estimated number of broken wires up to a rope distance of about 4500 mm is very good. Beyond this distance, there is an offset, which is probably due to a distance measurement error during disassembly of the rope.

A destructive break test of the rope showed a 30.2% loss of breaking strength. On the other hand, the second layer of strands of the rope (see Figure 11) represents about 30% of the total rope cross-sectional area. This leads to the hypothesis that, for this rope, the second layer of strands has lost all load-bearing capability.

The lack of sufficient information on the rope's operating history – and that of its predecessors – made this rope evaluation difficult. Under normal circumstances, these details are known and must be considered when assessing the rope condition. Altogether, this evaluation shows that a quantitative defect characterization for

ropes with internal broken wires and clusters of broken wires is possible. The example illustrates the capabilities and limitations of EM wire rope inspection methods for this particular defect characterization problem.



Example 3. Mooring rope inspection

This example deals with the inspection of an IWRC (Independent Wire Rope Core) mooring rope with a diameter of 89 mm whose inspection is depicted in Figure 1.

Figure 14 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 interstrand 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.¹³) 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 in the core wires leading to large numbers of fatigue breaks. These breaks can be very close together and can form groups of breaks. Eventually, the IWRC can completely disintegrate into short pieces of wire about half a lay length long.

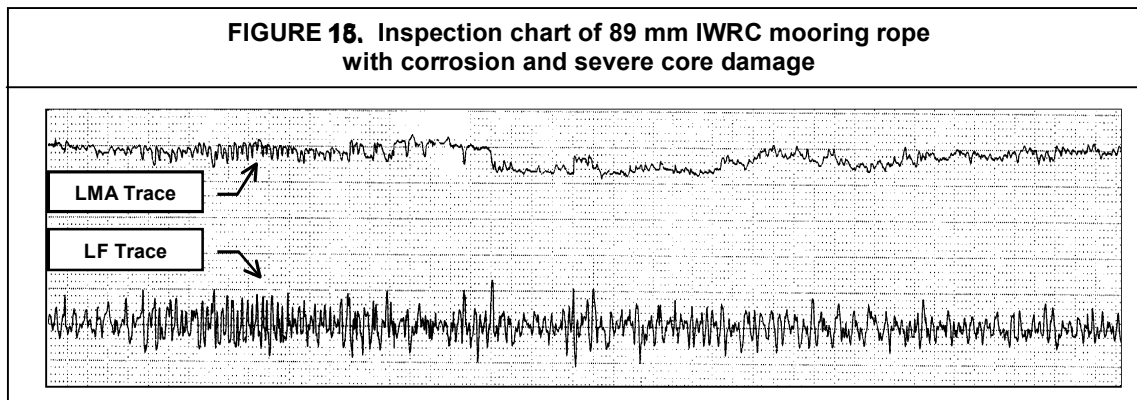


Figure 15 shows the results of the present mooring rope inspection. The chart recording indicates a severe breakup of the independent wire rope core, which is strong evidence of heavy fluctuating tensile fatigue loading. Note that the LMA and LF traces show the typical patterns of broken and missing wires (see Figure 3). The *missing wire* patterns indicate that short pieces of broken IWRC wires might have fallen out of the rope. In addition, together with the findings of a visual inspection, the chart indicates severe corrosion, including corrosion pitting. Note that corrosion products are clearly visible in Figure 1.

Summary and Conclusions

For most offshore ropes, inspection solely by visual methods is either unsafe or not practical. On the other hand, electromagnetic (EM) inspections at regular intervals can significantly increase confidence in the integrity of offshore ropes. Similar to other industries, the offshore oil and gas industry could derive considerable benefits from EM inspections.

EM inspections are particularly effective when they are combined with visual examinations as part of a comprehensive inspection program. For a thorough inspection, all aspects of a rope's condition must be considered, including

1. the findings of a visual inspection,
2. the results of an EM rope inspection,
3. the rope's operating conditions and damage mechanisms,
4. the history of the rope under test and that of its predecessors.

A program of periodic inspections is especially effective. In particular, periodic EM inspections allow the documentation of a rope's deterioration over its entire service life.

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