Magnetic Flux Leakage (MFL) Wire Rope Inspection: A Critical Review

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Abstract

When a wire rope is magnetically saturated in the axial direction the magnetic flux in the rope is proportional to its metallic cross-sectional area. This phenomenon is used for in-service wire rope inspections to measure the loss of metallic cross-sectional area (LMA).

There are two specific types of sensors that can be used to measure or estimate the magnetic flux in a rope: (i) Coils in combination with integrators and (ii) Hall sensors. This paper discusses the advantages and disadvantages of these devices when used to implement magnetic flux leakage wire rope inspection instruments.

The concepts of **Signal Fidelity** and **Wire Rope Roughness (WRR)** are introduced, and their significance for the inspection of modern wire ropes is elucidated.

The signal fidelity of **Hall sensor** based wire rope testers is compromised by high noise levels and, consequently, mediocre signal-to-noise ratios. In order to reduce noise levels, signals are typically low-pass filtered, which, on the other hand, degrades signal resolution and makes test results dependent on inspection speed.

In contrast, **coil-with-integrator** based instruments offer high resolution signals with near perfect signal-to-noise ratios. These signals do not require low-pass filtering, and they qualify as high-fidelity signals. Therefore, they can be used not only to detect but also to measure and characterize internal rope deterioration such as corrosion pitting, broken wire clusters, fretting, etc.

In addition to the LMA signal, all wire rope test instruments offer a so-called ***localized flaw (LF)*** signal. This signal is intended to show rapid changes of the rope cross-section that are typically caused by broken wires and/or corrosion pitting. While the LF signal can frequently indicate single and isolated broken wires, its usefulness is limited. For example, it cannot be used to assess the number of closely spaced broken wires in clusters and/or to evaluate the severity of corrosion pitting.

Introduction

While the majority of commercially available rope testers are useful tools in the rope inspector's toolbox, their performance varies over a wide range and is generally not sufficiently understood. As a result, some misconceptions and misunderstandings persist. Therefore, a review of different commercially available rope testers including their operating principles and their inspection accuracy appears opportune.[1]

There are essentially two different types of sensors available for the design and manufacture of wire rope testers

- Hall Sensors and
- Coils together with Integrators (Coils-with-Integrators).

At NDT Technologies, we have experimented with both, Coils-with-Integrators and Hall Sensors for many years, and we hold patents[2] and pending patents[3] for rope testers with both types of sensors. Backed by this wide-ranging experience, we can speak with some authority in reviewing the advantages and problems of various approaches.

Signal Quality

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 and wear.
- *Localized-Flaw (LF) Inspection*, which can (qualitatively) detect external and internal discontinuities such as broken wires and corrosion pitting. However, the usefulness of the LF signal is extremely limited. For example, while this signal can indicate single and isolated broken wires, it cannot be used to determine the number of closely spaced broken wires in clusters or to assess the severity of corrosion pitting.

Rope testers that can simultaneously produce LMA and LF signals are called *dual function* instruments.

In order to compare the performance of rope testers, the term *Signal Quality* must first be defined. This is done in the following.

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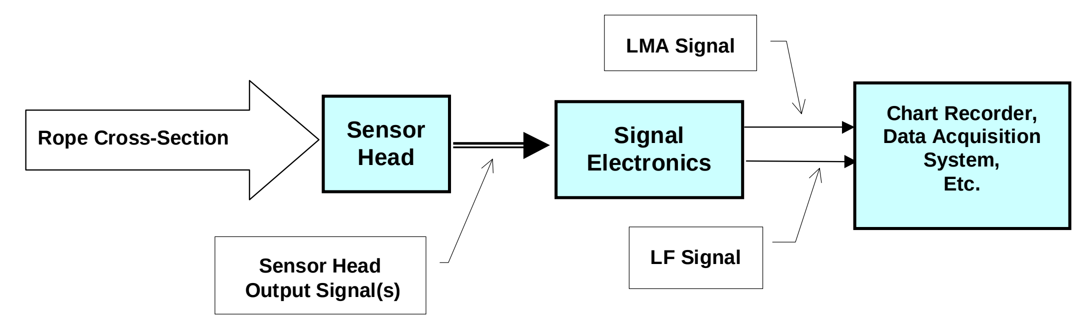
[1] The performance as well as the underlying operating and physical principles of the Chinese TCK wire rope testers are dubious. Because the operation of this equipment is shrouded in secrecy, it will be excluded from the present discussion.
[2] http://dl.dropbox.com/u/46302745/Patents/First%20Rope%20Tester%20Patent%2004659991_1.PDF,
[3] http://dl.dropbox.com/u/46302745/Patents/US20100148766_1.PDF

The Functional Block Diagram of Figure 1 illustrates the signal generation process. This figure shows the rope's cross-sectional area as the input to an EM wire rope inspection system. From this input, the sensor head produces one or several electrical signals. These signals are electronically processed to produce the LF and LMA signals that are recorded by a chart recorder and/or stored by a data acquisition system.

In other words, the *metallic cross-sectional area* – or the *loss of metallic cross-sectional area* – of the wire rope under test can be considered the input signal, and the LMA and LF signals can be considered the output signals.

FIGURE 1. Block diagram of the signal generation process



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 of metallic cross-sectional area* 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* are collectively 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*[4] applies. This means that, since a defect can be represented as the sum of several *fundamental defects*, the corresponding LMA and LF signals are the sum of the corresponding *fundamental LMA* and *LF signals*.

Therefore, the performance of an instrument is completely defined by its *step response*, and determining and evaluating the *step response* is a concise method for characterizing the performance of an EM wire rope tester.

These concepts are elucidated further by Figure 2, which illustrates the *step response* of an idealized instrument. The figure depicts the rope cross-section as the input signal and the idealized corresponding LMA and LF output signals.

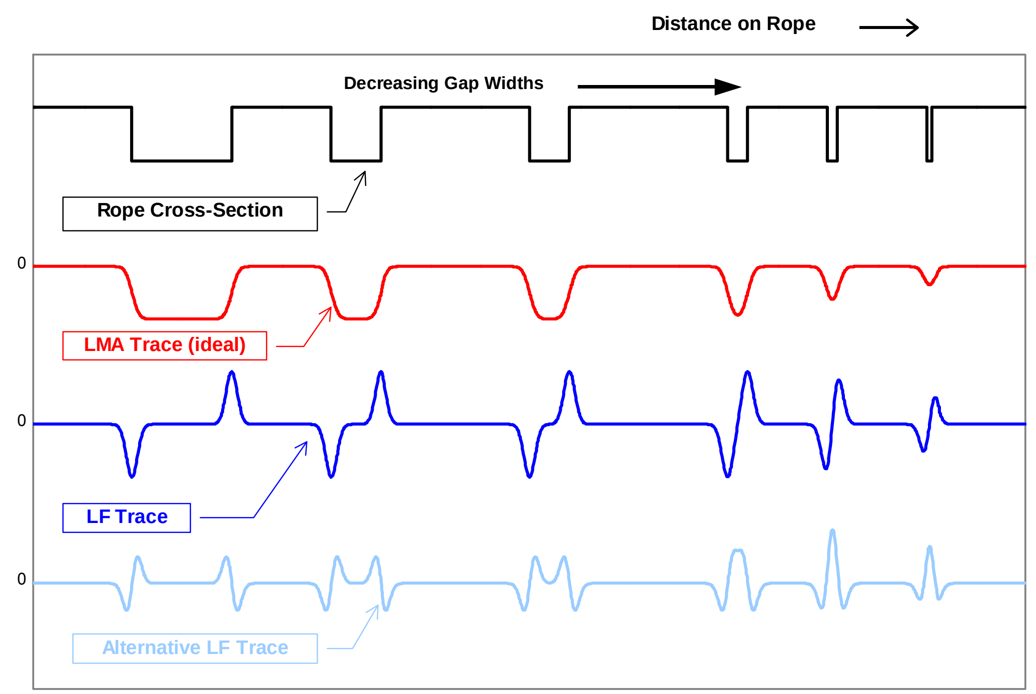
Any inspection equipment should present data in a form that facilitates their interpretation by the human operator. Figure 2 shows that a perfect LMA signal could serve as such an accurate and conceptually simple map of a rope's LMA that is easy to interpret by the inspector

[4] http://en.wikipedia.org/wiki/Superposition_principle

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, shown as *Alternative LF Signal* in Figure 2.

However, a typical LF chart recorder signal of a broken wire has positive and negative going sections. 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. Therefore, the LF signal is of limited use for estimating the number of broken wires in clusters and will not be discussed in further detail.

FIGURE 2. Input and output signals of an idealized rope test instrument



Signal Fidelity

The dictionary defines ***Signal Fidelity*** as the degree to which an electronic system accurately reproduces its input signal.[5]

For the present discussion, the following two aspects of **Signal Fidelity** will be considered:

- **Quantitative Resolution** or **Averaging Length**. (The required minimum length of a uniform change of metallic cross-sectional area for which a sensor provides an accurate quantitative measurement of a rope's LMA.[6])
- **Distortion**. (An undesired change in the waveform of a signal.[7])

[5] http://en.wikipedia.org/wiki/Fidelity
[6] http://dl.dropbox.com/u/46302745/Quantitative%20LF/WRR%20Paper/CRITREV.PDF
[7] http://en.wikipedia.org/wiki/Distortion#Electronic_signals

Following this interpretation, the LMA signal of Figure 2 is considered to have a very high **Quantitative *Resolution*** (or short ***Averaging Length***) and no ***Signal Distortion.*** Therefore, by definition, it is considered a ***High-Fidelity Signal***. Accordingly, LMA signals similar to the LMA signal in Figure 2 will be referred to as ***High-Fidelity Signals*** in the following.

Using some engineering finesse, coil-with-integrator systems can be made to produce a high-fidelity signal as defined above.

In contrast, producing a high-fidelity LMA signal is next to impossible for state-of-the-art Hall-sensor-based wire rope testers.

Operating Principles

For all dual-function instruments, strong permanent magnets induce a magnetic flux at the saturation level in the rope in the axial direction. Various types of sensors, such as coils or Hall 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. Differential sensors cannot detect more gradual changes of the rope flux, which are typically caused by wear and corrosion.

The *axial* component of the leakage flux can be measured by *axial* sensors. This *axial* leakage flux signal is frequently offered as an LMA signal. However, while the *axial* signal can be useful for qualitative defect characterization, it is very complex and cannot be directly used to ascertain the LMA of a rope. Therefore, instruments that use this approach are not strictly of the dual-function type as defined above.

Methods for the (quantitative) measurement of the LMA of a rope are discussed below.

As mentioned previously, two types of sensors can be used to measure magnetic flux:

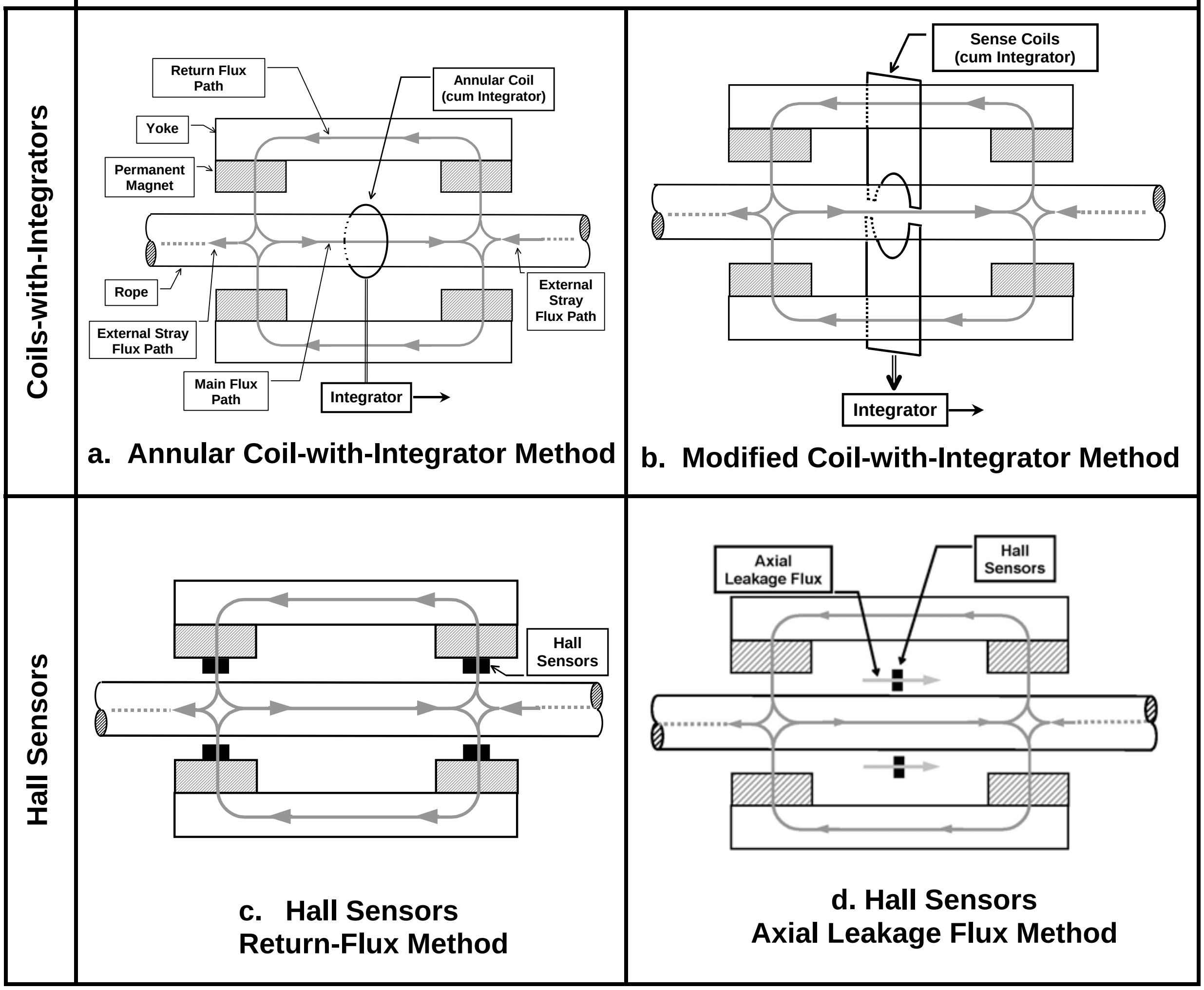
- Hall sensors and
- coils in combination with electronic integrator circuits.

To measure flux density, **Hall 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 a rope. Therefore, instruments that use Hall 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-with-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, the two above mentioned basic methods are used for the determination of LMA. They are illustrated in Figure 3.

FIGURE 3. Cross-sectional area measurement methods



Coil-with-Integrator Methods

The ***Annular Coil-with-Integrator Method*** uses an annular coil together with an electronic (or digital) integrator circuit to determine the local magnetic flux inside the rope (Figure 3a). Note that the coil must encircle the rope.

Since it measures the magnetic flux inside the rope directly and locally, the annular coil approach offers uncommon inspection accuracy. The LMA ***signal fidelity*** offered by this approach is equal to that of the idealized **high-fidelity** LMA signal shown in Figure 2. 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 this 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 inherent 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 Coil-with-Integrator Method***, shown in Figure 3b, tries to retain the superior performance of the *Coil-with-Integrator Method* while allowing the implementation of hinged sense heads of the *clamshell* design.

In contrast to the above described main-flux approach, the modified main-flux method allows the design of hinged sensor heads of the *clamshell* type. This feature makes it easy to attach the sensor head to a rope even under adverse field conditions.

The test signals of this *Modified Coil-with-Integrator Method* are a combination of the *Coil-with-Integrator* signal and a signal component that is caused by the (parasitic) *outside stray flux*[8]. Unfortunately, this *outside signal component* is significant. It compromises the quality of the test results and must be considered parasitic.

Fortunately, this parasitic effect can be almost completely eliminated by a computer procedure – called ***Signal Enhancement*** or ***Echo Cancellation*** algorithm.[9] This way, the *Modified Coil-with-Integrator Method* retains the desirable features of the *annular coil* approach.

After Signal Enhancement, the LMA signal quality offered by this approach is equivalent to that of the *Annular Coil-with-Integrator* approach. This means that the LMA signal obtainable by the *Modified Coil-with-Integrator Method* is a ***high-fidelity*** signal as defined above.

Hall Sensor based Methods

The ***Return Flux Method*** uses Hall sensors to measure the magnetic flux in the magnetic return path of the instrument. Illustrated by Figures 3c, the return flux is equal to the *average value of the axial rope flux* inside the sensor 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 are usually inserted into the air gap between the permanent magnet poles and the rope.

The *averaging length* for this approach is closely related to the length of the sensor head which implies a poor *quantitative resolution* and, therefore, **low *signal fidelity*.**

[8] That portion of the flux that leaves and enters the sense head to and from the outside, respectively, and that flows along some external stray flux path as indicated in Figure 3

[9] http://dl.dropbox.com/u/46302745/Quantitative%20LF/WRR%20Paper/Paper%20Krakow.pdf

Axial Leakage Flux Method **–**The *axial* component of the leakage flux can be measured by *axial* sensors (Figure 3d)*.* Easy and straightforward to implement, axial leakage flux sensing is popular among designers of EM wire rope test instruments. In the absence of more accurate LMA measurement capabilities, the *axial leakage flux* signal has been offered in lieu of and as an "LMA Signal." However, as discussed in the following, the *axial leakage flux method* inherently suffers from **signal distortions.** Therefore, it is not a **high-fidelity signal** as defined above.

The signal generation processes will be discussed further in the next chapter.

Signal Generation and Experimental Results

Coil-with-Integrator Methods

To illustrate the *annular coil* approach, Figure 4 shows the LMA and LF traces of a laboratory test rope. The LMA and LF signals were acquired with an annular coil and a modified coil as shown in Figure 4a and 4b, respectively. Short pieces of wire, attached to the rope, simulate anomalies. The attached wires have different lengths as indicated. They typically represent a 1% increase of metallic cross-sectional area. (The LMA caused by the internal wire is unknown). The two ends of the rope are welded together to form an infinite loop. The weld is also indicated in the chart.

Figure 4a shows the excellent results that could be obtained with annular coils. This means, the increases of metallic cross-sectional area caused by the attached wires are clearly indicated with their full magnitude for wires that are longer than about 50 mm. The metallic cross-sectional area changes caused by shorter wires are also indicated, albeit not to their full extent.

These test results show that the *annular coil* approach offers uncommon resolution and signal fidelity. In fact, the test signals of this method closely resemble the idealized results of Figure 2.

Figure 4b shows the test signal generated by the Modified Coil Method shown in Figure 3b. As mentioned previously, 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 and flows along some external stray flux path (see Figure 3). Unfortunately, this *outside signal component* is significant. It compromises the quality of the test results and must be considered parasitic. A close examination of the LMA signal shows that the *outside signal component* is generated as a discontinuity enters and leaves the sensor head, respectively. This parasitic *outside signal component* resembles the main signal component with a smaller amplitude as illustrated by Figure 4b.

FIGURE 4a. Step responses for annular coil method

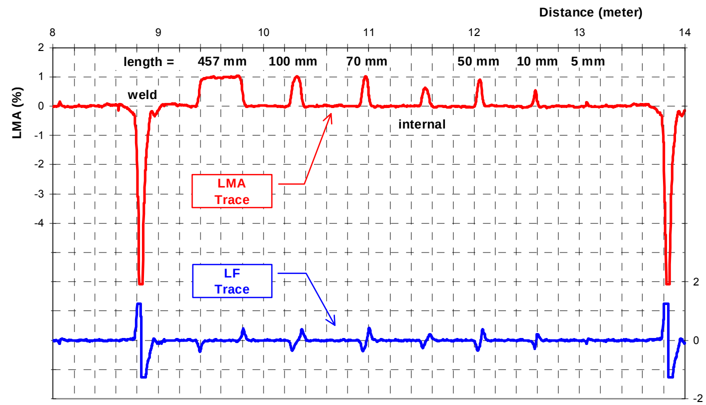


FIGURE 4b. Step responses for modified coil method

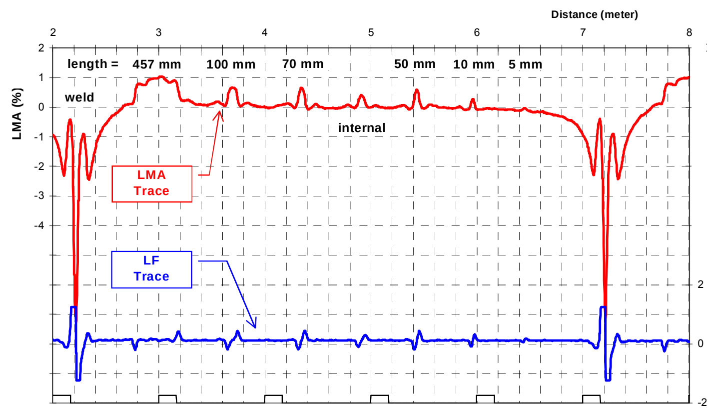
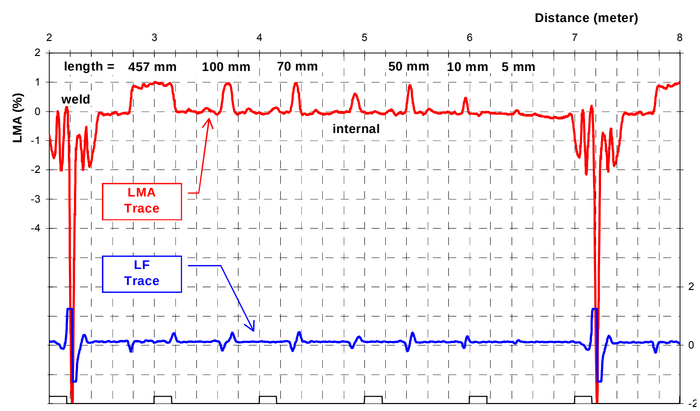


FIGURE 4c. Step responses for modified coil method after computer enhancement



The physics of this parasitic effect is well understood. It can be minimized by using the so-called *signal enhancement* or *echo cancellation* algorithm[10] that is implemented as part of the NDT_CARE™ (<u>C</u>omputer-<u>A</u>ided <u>R</u>ope <u>E</u>valuation) software from NDT Technologies, Inc. *Signal enhancement* is illustrated by Figures 4b and c. Figure 4b shows the LMA trace, before *signal enhancement*, that was acquired with a sensor head of the *auxiliary coil* type. Here, the indicated change of cross-section depends on the length of the anomaly as illustrated. This means that area changes caused by short anomalies are not indicated to their full extent.

Figure 4c shows that, after enhancement (with the above-mentioned *Enhancement Algorithm*) all metallic area changes that extend over lengths greater than 50 mm are correctly measured. In other words, the *averaging length* (or *quantitative resolution*) is now 50 mm, which equals the quantitative resolution of the annular coil approach illustrated by Figure 4a.

This means that, after signal enhancement, the LMA signal available from the *Modified Coil-with-Integrator Method* qualifies as a ***high-fidelity*** signal as defined above.

<u>Long-term integration</u>. To produce an LMA signal, the coil-with-integrator method requires integration of the coil voltage. A problem is caused by the fact that plain analog integration circuits or digital integration algorithms will drift when integration is performed over long time periods. This problem is caused by small offsets and/or random variations of the integrator input signal and/or by small imperfections if the integrator arrangement.

This behavior can be eliminated by integrator balancing circuits or algorithms.

NDT Technologies, Inc. uses a proprietary balancing method that allows low-error operation over long time periods. This allows an accurate determination of LMA, with small errors that are well within the accuracy limits of the entire magnetic measurement method. Percentagewise, this error declines as the rope diameter increases. Moreover, the integrator error is gradually reset to zero when rope sections with no deterioration are inspected.

It is sufficient to adjust the balance settings of the integrator once during assembly for the life of the equipment. It is possible – but not necessary – to rebalance the integrator anytime if desired. Rebalancing can be manual or automatic by a computer algorithm.

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[10] Weischedel, H.R., *"Electromagnetic Wire Rope Inspection: Signal Generation, Filtering, and Computer-Aided Rope Evaluation."* Presented at *<u>The Nondestructive Testing of Rope.</u>* Krakow, Poland: (O.I.P.E.E.C.) International Organization for the Study of the Endurance of Wire Rope. (September 1999) http://www.ndttech.com/Papers/Signal%20Generation%20Filtering.pdf

Detection and Quantitative Characterization of Internal Corrosion Pitting and Broken Wire Clusters

NDT Technologies, Inc. has recently introduced a new inspection and analysis method for assessing and quantitatively characterizing wire rope degradation that is caused by external and, especially, internal corrosion pitting and clusters of broken wires.[11]

This significant capability adds an important new tool to the rope inspector's toolbox.

To implement the analysis procedure, a new concept called *Wire Rope Roughness (WRR)* was introduced. WRR is defined as the surface roughness of the aggregate wires of a rope, including corrosion pitting, broken wires and clusters of broken wires. WRR is determined by extracting the WRR signal from the LMA signal.

Extraction of a high-quality WRR signal calls for a **high-fidelity** LMA signal with excellent resolution and without low-pass filtering to start out with. This signal must record accurately even small-scale high-frequency features on the aggregate wire surface.

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.

Furthermore, it is desirable to remove from the LMA signal artifacts that are introduced by the sensor head geometry. This is accomplished by the **Signal Enhancement** (or **Echo Cancellation**) procedure that has been described above.

The **WRR Analysis** procedure is now integrated in the NDT_CARE™ (**C**omputer-**A**ided **R**ope **E**valuation) software, and it can be routinely used for electromagnetic wire rope inspections.

For details on the **WRR Analysis** method please refer to a companion paper titled "Nondestructive Wire Rope Inspection: Detection and Quantitative Characterization of External and Internal Corrosion Pitting and Broken Wire Clusters." [12]

Hall Sensor Based Methods

Signal-to-Noise Ratio

Hall Sensor based systems are plagued by problems with signal-to-noise ratios.

Problems are caused by relatively small amplitudes of rope discontinuity signals, at the mV level, and by **inherent** wide-band noise, also at the mV level, that is produced by the Hall sensors themselves.

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[11] Internal broken wires and wire clusters typically occur in non-rotating and IWRC ropes that are used, for example, as crane ropes. Corrosion pitting 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 rope.

[12] Weischedel, H.R., *"Nondestructive Wire Rope Inspection: Detection and Quantitative Characterization of External and Internal Corrosion Pitting and Broken Wire Clusters,"* Report NDT Technologies, Inc., 2012.

Moreover, rather than sensing the total magnetic flux inside the rope, Hall sensors can sense only magnetic flux densities in discrete locations along the circumference of the rope.

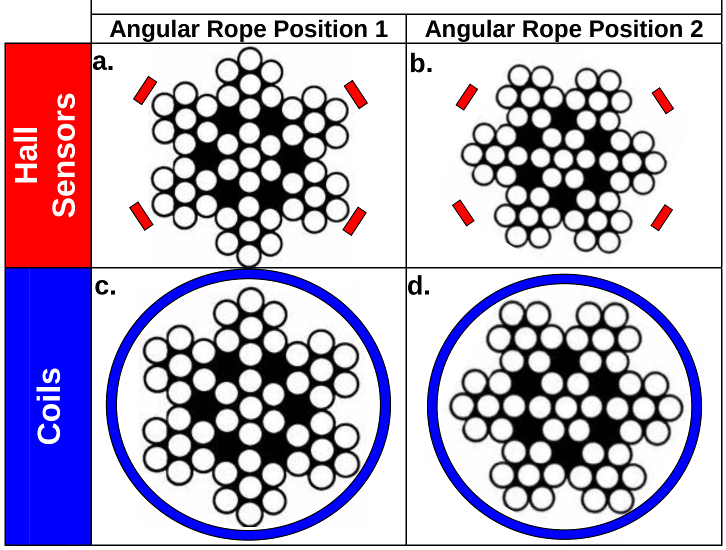
A wire rope consists of many wires and strands that are laid into the rope in a complex fashion. This arrangement creates many external and internal inhomogeneities. Because of the inhomogeneous rope structure – even of new ropes – Hall sensors pick up the noise that is caused by the uneven arrangement of its wires and strands as a rope moves through the sensor head.

This phenomenon, commonly called **rope noise**, is illustrated by a simple example as shown Figures 5 a and b. For stranded ropes several strands are laid helically in one or more layers around a core. As shown in the figure, because of this helical arrangement, the rope's cross-section assumes different angular positions relative to the Hall sensors as it moves through the sensor head.

The magnetic leakage flux surrounding the rope near the Hall sensors changes accordingly. Caused by this changing leakage flux, the Hall sensor signals vary considerably as the rope moves through the sensor head even for a new and undamaged rope. Since these varying signal components are not caused by rope deterioration, they must be considered noise.

Usually flux collectors made from ferromagnetic steel are used to homogenize the magnetic flux distribution circumferentially. However, this approach only mitigates, rather than eliminates, the problem.

Figure 5. Angular rope positions



In contrast, coils circumscribe the rope. Therefore, coils-with-integrators sense the total combined magnetic flux in the rope, which – for new ropes – is independent of localized magnetic inhomogeneities inside the rope and circumferentially along the rope surface. In other words, the angular position of the rope inside the sensor head does not influence the signal. This situation is illustrated by Figures 5 c. and d.

Therefore, Coils-with-Integrators do not produce any inherent rope noise and offer a noise free LMA signal with a near perfect signal-to-noise ratio.

For these reasons, no low-pass filtering with its associated signal distortions is required. This, in turn, allows high-fidelity, high resolution test results.

The above described problem associated with Hall sensors is compounded by a phenomenon that will be described in the following.

Consider Figure 6, which shows the magnetic flux in the vicinity of a broken wire end. As illustrated, the ends of broken and missing wires represent magnetic flux concentrators that cause very high localized magnetic flux densities (in the radial as well as the axial direction) in the air space in the immediate vicinity of the wire tips.[13]

The axial and radial components of the concentrated flux are sensed by the Hall elements shown in Figures 3c and d. This, in turn, causes associated spikes with disproportionate amplitudes in the axial and radial signals. The problem is illustrated by Figure 7, which shows an axial signal 'step response' including the spike (impulse) caused by the step discontinuity (wire tip) of cross-sectional area.

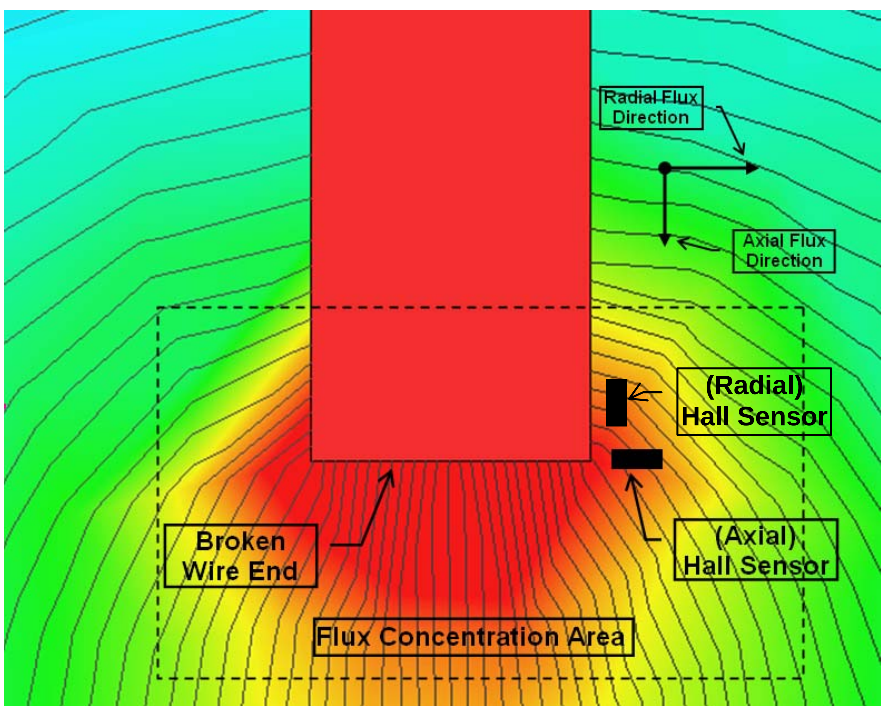


FIGURE 6. Flux concentration

[13] The rainbow color scale indicates the absolute value of the magnetic flux |B|).

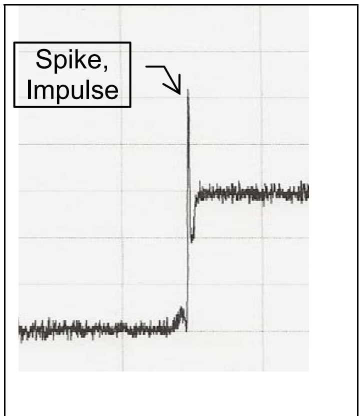


FIGURE 7. Spike in the axial Hall sensor signal

Furthermore, a wire rope consists of many wires that are laid into the rope in a complex fashion. This arrangement creates many internal and external inhomogeneities (discontinuities). The inhomogeneous rope structure creates numerous magnetic flux concentrators causing spikes with disproportionally large amplitudes in axial and radial Hall sensor signals.

This, in turn, makes these signals very noisy. The associated reduced signal-to-noise ratios compound the uncertainty and errors associated with the interpretation of Hall sensor signals.

To illustrate, the following figures show signals from an inspection performed with a Hall sensor based instrument.[14] Figure 8 shows the raw data. As discussed above, caused by the inhomogeneous rope structure combined with corrosion pitting, the test results show considerable noise levels with associated mediocre signal-to-noise ratios for both, the so-called LMA and the LF traces.[15]

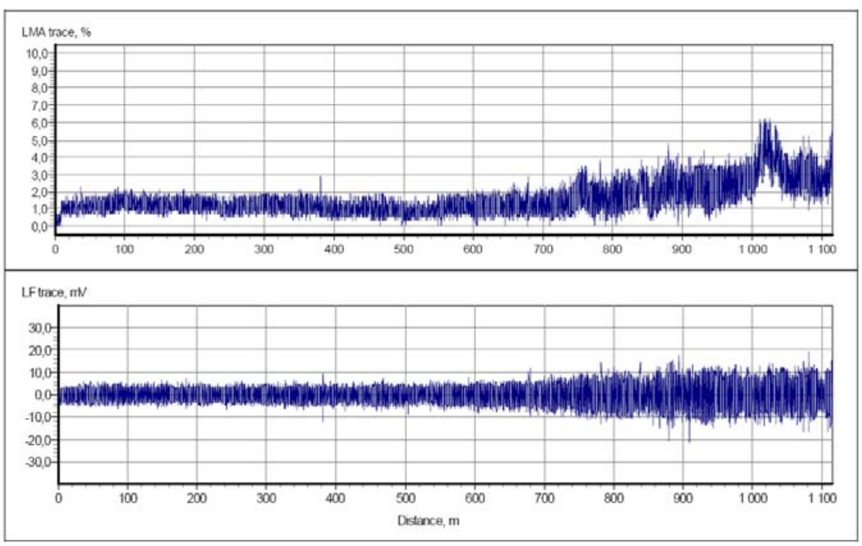


FIGURE 8. Hall sensor based inspection raw data

[14] http://www.intron.ru/getfile.phtml?id=24&lang=en

[15] http://www.ansys.co.za/Website%20pdfs/Mining%20and%20Industrail/CRMS%20Overview.pdf, page 4.

To remedy this situation, low-pass filtering is typically used to improve the appearance of the Hall sensor signals. However, in order to be effective the low-pass filter used must have a rather low cut off frequency,[16] which significantly distorts inspection signals. This means that low-pass filtering (or data averaging) reduces inspection accuracy (resolution) of any test results. For example, low resolution prevents the detection and evaluation of small but significant features in test results.

In addition, low-pass filtering makes the test results dependent on inspection speed.

Figure 9 shows the test results of Figure 8 after low-pass filtering.

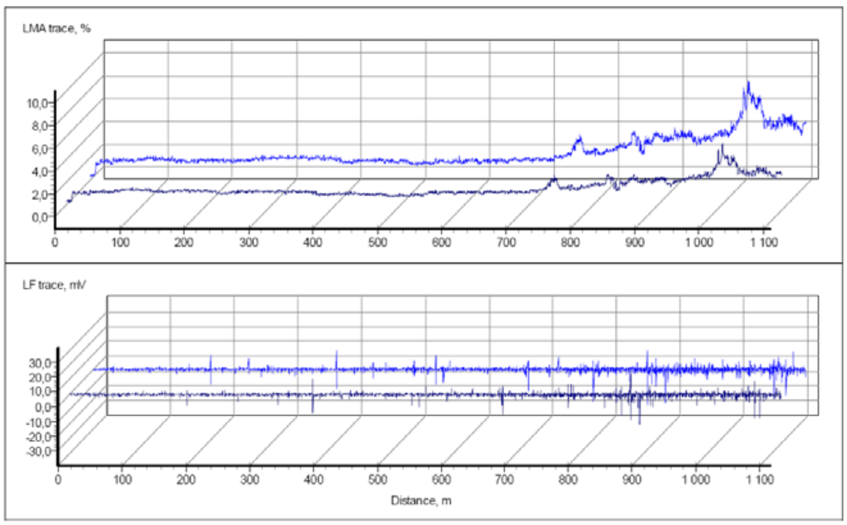
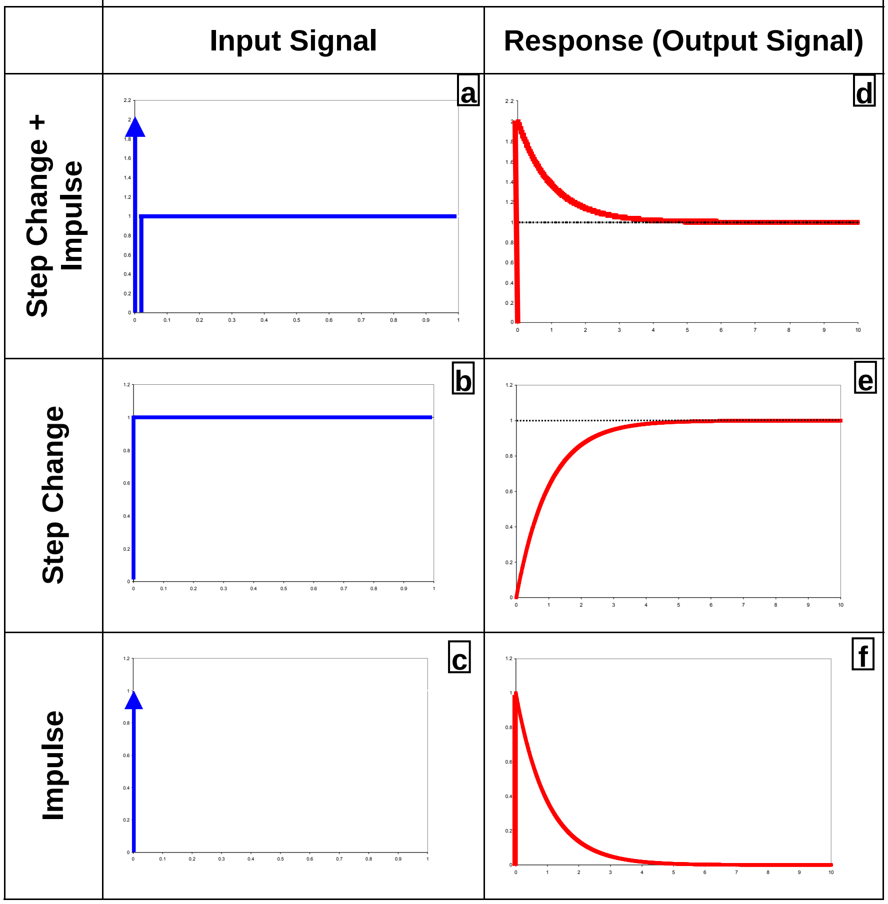


FIGURE 9. Inspection data after low-pass filtering

To elucidate the effects of low-pass filtering on Hall sensor type signals consider Figure 7. The wave shape of this signal can be represented – in an idealized form – as the sum of an impulse[17] and a step change[18] as shown in Figures 10 a-c. Figures 10 d-f illustrate the response of a simple 1st order low-pass filter to this signal. Note that this output signal shows considerable overshoot as shown in Figure 10 d. The problems associated with this type of signal response will be discussed below.

[16] http://en.wikipedia.org/wiki/Cutoff_frequency
[17] http://en.wikipedia.org/wiki/Impulse_response, http://en.wikipedia.org/wiki/Dirac_delta_function
[18] http://en.wikipedia.org/wiki/Step_response

FIGURE 10. 1st order low-pass filter response



Axial Leakage Flux Method – The *axial* component of the leakage flux can be measured by *axial* sensors (Figure 3d). Easy and straightforward to implement, axial leakage flux sensing is popular among designers of EM wire rope test instruments. In the absence of more accurate LMA measurement capabilities, the *axial leakage flux* signal has been offered in lieu of and as an “LMA Signal.” However, as discussed in the following, the *axial leakage flux* inherently is not well suited for measuring LMA.

Since Hall sensor generated signals are quite noisy, low pass filtering with a rather low cut-off frequency is always used. However, low pass filtering results in step responses – caused by missing or broken wires – with large overshoots similar to those depicted in Figure 10.

This figure illustrates the step response of a single Hall sensor caused by a single broken wire end. However, note that – compared to the responses shown in Figure 10 – actual *axial leakage flux* signals are usually more complex because they are generated by several complementary Hall sensors and more than one wire end.

FIGURE 11. Fundamental input and output signals of axial leakage flux sensors
("Quasi-LMA Signal")

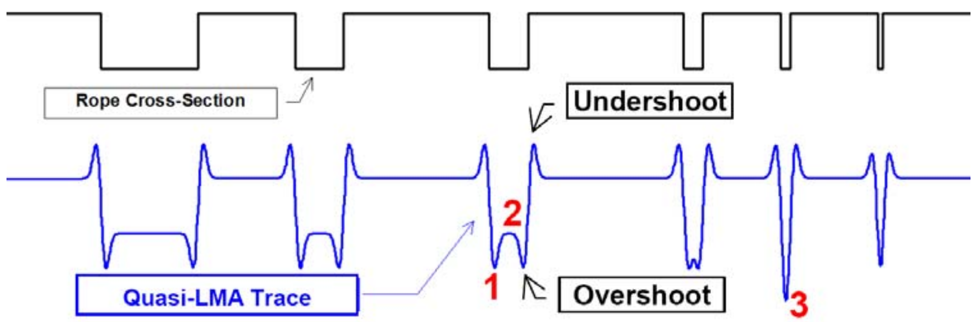


Figure 11 shows the typical step response of an *axial leakage flux* signal.[19] As illustrated, this signal suffers from a serious problem: Its *step response* shows large overshoots in both directions. This peculiarity makes it impossible to determine the actual LMA from the *axial leakage flux signals*, even for simple changes of metallic cross-section with uncomplicated geometrical shapes. The figure shows that the *indicated LMA*, as measured by the *axial flux signal*, can be much bigger or significantly smaller than the *actual LMA*.

For example, in Figure 11, which of the indicated LMA values in locations 1 or 2 should be used for estimating the actual LMA? Moreover, the indicated LMA in position 3 is greater than all the other indications. This means that broken wires with a certain gap width will produce disproportionally large LMA indications. Therefore, the axial leakage flux signal depends to a great extent on the actual LMA geometry.

Because this type of performance is not well suited for a rational and acceptably accurate calibration and LMA estimation, axial flux signals could be called "*Quasi-LMA*" signals. For Quasi-LMA signals, a rational quantitative chart evaluation is not possible. Interpretation depends on the operator and is usually based on guesstimating.

In contrast to the simple step changes of metallic cross-section shown in Figure 11, actual changes of a rope's metallic cross-section have rather complicated geometries. Accordingly, the corresponding axial leakage flux signals will be very complex and difficult – or impossible – to interpret.

In the field, a wide variety of deterioration modes interact in a very complex fashion to produce a Quasi-LMA signal. For example, while a uniform LMA that extends over a certain length of a rope could be correctly indicated by a Quasi-LMA signal, more irregular shaped LMA, caused for example by clusters of broken

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[19] T.S. Golosinski, A. Tytko, "Magnetic Examination of Wire Ropes: Loss-of-Metallic Area (LMA) Measurement with Hall-Effect Sensors," OIPEEC Bulletin 75, June 1998.

wires or corrosion combined with corrosion pitting, can no longer be measured with a sufficient degree of accuracy.

Because of this, LMA measurements using the *axial leakage flux* for in-situ rope inspections are ambiguous, and, more often than not, erroneous.

Moreover, a rational LMA calibration method for the *axial leakage flux signal* cannot be developed. Therefore, instruments that use this approach are not of the dual-function type as defined above.

In addition to the above mentioned problems, low pass filtering makes calibration speed dependent. This adds another level of ambiguity.

The **Return Flux Method** uses Hall sensors to measure the magnetic flux in the magnetic return path of the instrument. Illustrated by Figure 3c, 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 sensor head. The *averaging length* for this approach is closely related to the length of the sensor head which implies a rather poor *quantitative resolution*.

As mentioned previously, *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 a rope's LMA.

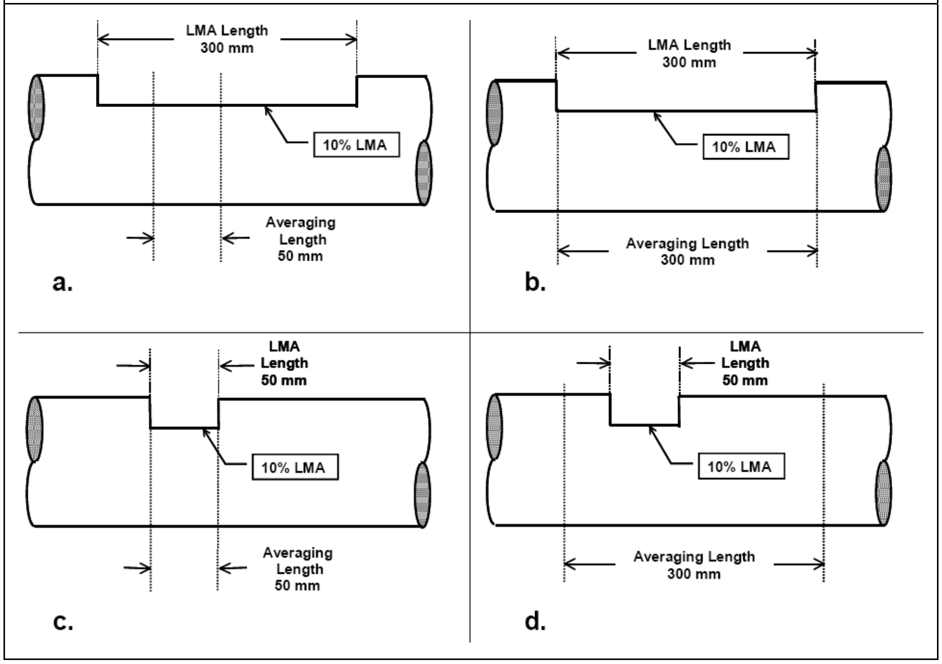
To visualize the concept of *quantitative resolution* or *averaging length*, assume that, instead of measuring metallic cross-sectional area directly, the rope tester continuously measures the metallic volume of consecutive rope sections with lengths that are equal to its *averaging length*. Figure 12 illustrates this concept.

Figure 12 a 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 12 b, 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 12 c 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 12 d, an instrument with a 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 a*veraging length.*

Note that signal averaging is a quintessential type of low-pass filtering, and that signals can lose a significant amount of information (details) by low-pass filtering.

FIGURE 12. LMA length and averaging length

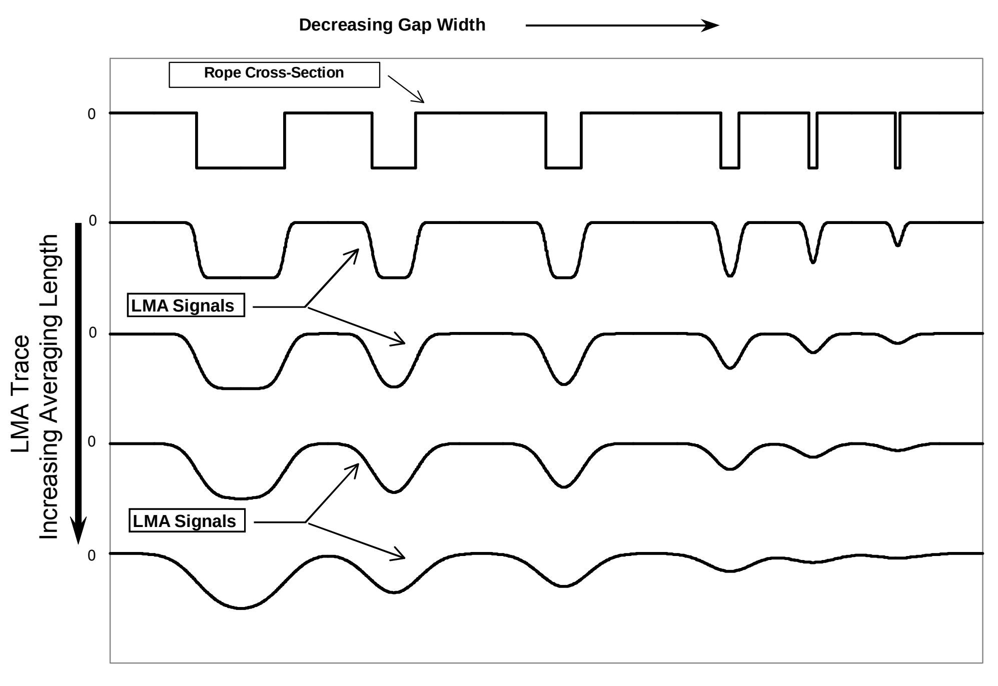


An analogy can illustrate the problems associated with long LMA averaging lengths: A chain is only as strong as its weakest link. Obviously, the strength of a chain is not determined by the average strength of some of its links. Similarly, the strength of a rope, which has lost metallic cross-section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

Figures 13 and 14 illustrate this situation. They show how the quality of LMA signals deteriorates as the LMA averaging length increases.

FIGURE 13. LMA signals as a function of averaging length



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 12, the concept of *quantitative resolution* or *averaging length* is important for specifying and comparing the performance of rope testers.

For different rope testers, averaging lengths can vary over a wide range. For example

- Typical *Averaging Lengths* of *Coil-with-Integrator* type rope testers from NDT Technologies, Inc. – including *Signal Enhancement* – are 50 mm (See Figure 4 c).
- The *Averaging Length* of a *Return Flux* signal is typically equal or longer – and sometimes much longer – than the length of the sensor head used.[20]

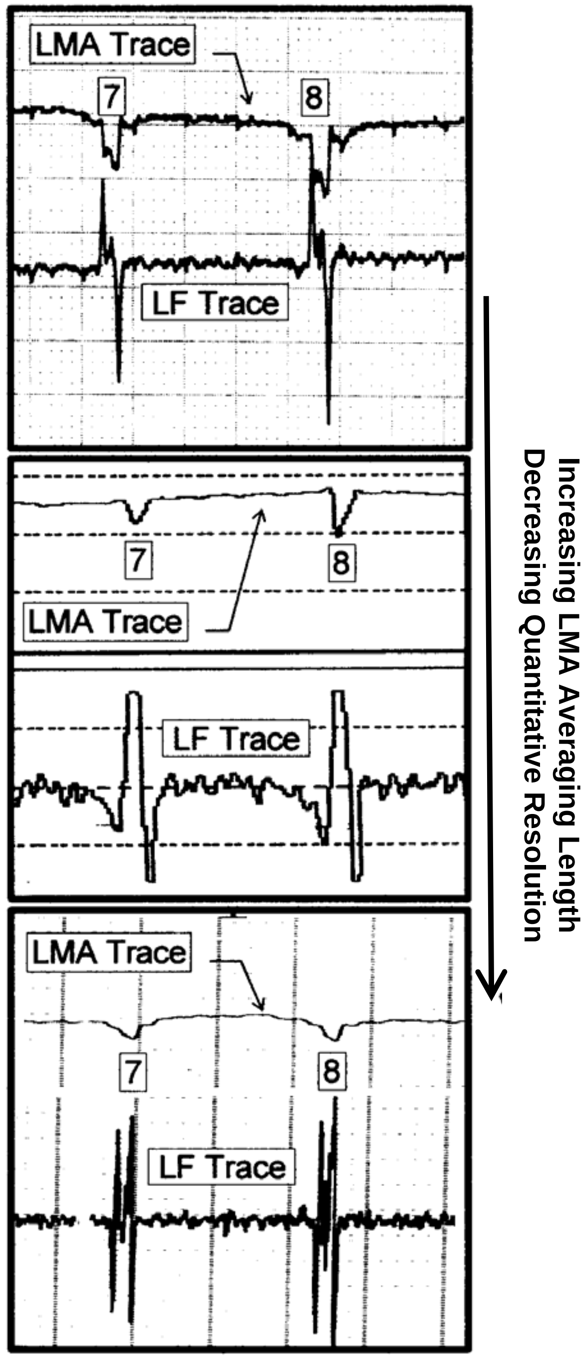
[20] http://www.ansys.co.za/Website%20pdfs/Mining%20and%20Industrail/CRMS%20Overview.pdf, page 4.

FIGURE 14. LMA and LF traces of rope test instruments from three different manufacturers[21]

NDT Technologies, Inc.
LMA-175
(Coil-with-Integrator Type)

Wire Rope
Tester X
(Return Flux Type)

Wire Rope
Tester Y
(Return Flux Type)



[21] Weischedel, H.R. *"Magnetic Flux Leakage Inspection of Wire Ropes."* Lecture Notes. http://dl.dropbox.com/u/46302745/Notes.pdf

Summary and Conclusions

Two different types of sensors can be used to measure or estimate the magnetic flux in a rope: (i) Coils in combination with integrators and (ii) Hall sensors. The advantages and disadvantages of these devices for the implementation of magnetic flux leakage wire rope inspection instruments were discussed.

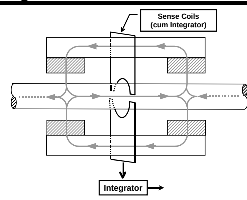
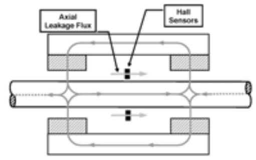
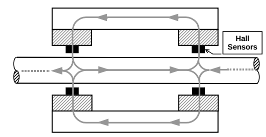
The significance of **Signal Fidelity** for the evaluation of electromagnetic wire rope inspection equipment was elucidated.

Wire rope testers that are based on Hall sensor technology are plagued by high noise levels and, consequently, low signal-to-noise ratios. To improve the appearance of LMA and LF signals, low-pass filtering is typically used. Mediocre signal-to-noise ratios combined with low-pass filtering compromise Hall sensor based signals. Therefore, these signals are not of the **high-fidelity** type as defined in the present paper.

In contrast coil-with-integrator signals have near-perfect signal-to-noise ratios. Therefore, low-pass filtering is not required. After Echo Cancellation (or Signal Enhancement), coil-with-integrator based LMA signals qualify as **High-Fidelity** signals.

In turn, this high-fidelity signal can be used to perform a (quantitative) **Wire Rope Roughness (WRR) Analysis** in order to determine the extent and the severity of internal deterioration such as corrosion pitting, clusters of broken wires, etc.

Table 1 lists and compares salient features of various rope tester types from several manufacturers.

TABLE 1. Salient features of different types of rope testers			
Sensor Device	Coil-with-Integrator	Hall Sensor	
Type	Modified Coil + Signal Enhancement[22]	Axial Leakage Flux[23]	Return Flux[24]
Schematic[25]			
Averaging Length[26]	50 mm	Not Applicable (Depends on LMA Geometry)	≈ Length of Sensor Head +
Signal Distortion[27]	None (With Signal Enhancement)	High	Low Resolution
LMA Calibration[28]	Yes	Not Possible	Yes (Low Resolution)
Inherent Device Noise [29]	None	Wide Band	
Rope Noise[30]	Low	Very High	
Low-Pass Filtering[31]	None	Yes	
High-Fidelity[32] Signal	Yes	No	
LF Signal[33]	Yes (Limited Usefulness)		
Quantitative LF Signal[34]	WRR Analysis[35] (Pat. Pend.)	Not Possible	Not Possible
Manufacturers	NDT Technologies, Inc.	Intron Zawada	Heath & Sherwood Rotesco
		ANSYS (South Africa)	

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[22] pp. 8-9
[23] pp. 16-18
[24] pp, 18-21
[25] c.f. Figure 3
[26] pp. 18-21
[27] pp.8-10, 16-17
[28] p. 18
[29] p. 11
[30] pp. 12-16
[31] pp. 16-18
[32] pp. 3-4
[33] pp. 3, 4, 11
[34] p. 11
[35] Weischedel, H.R., *"Nondestructive Wire Rope Inspection: Detection and Quantitative Characterization of External and Internal Corrosion Pitting and Broken Wire Clusters,"* Report NDT Technologies, Inc., 2012.