Electromagnetic Wire Rope Inspection:
Signal Generation, Filtering, and Computer-Aided Rope Evaluation

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Summary

This paper first discusses the inherent signal generation and filtering processes that occur in electromagnetic (EM) wire rope testers. Then it considers and evaluates electronic methods for processing and manipulating the test results.

1. Introduction

EM wire rope inspection instruments have been developed over the past 90 years. The operational principles of electromagnetic wire rope testers were reviewed extensively in some of the author's previous publications (Weischedel 1985, Weischedel 1987, Weischedel 1990b). Two different and distinct 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 LMA, such as corrosion and wear.
- Localized-Flaw (LF) Inspection, which (qualitatively) detects a wide variety of external and internal discontinuities such as broken wires and corrosion pitting.

Modern dual-function EM rope testers allow simultaneous LMA and LF inspections.

2. Data Processing and Filtering

Modern integrated electronic circuitry and personal computers, together with electromagnetic rope inspection instruments, allow the easy implementation of algorithms for wire rope evaluation. If properly used and implemented, these algorithms can be quite effective. They can greatly facilitate the assessment of the condition of wire ropes.

Potential functions of computer based wire rope evaluation systems can be grouped into several categories as follows.

1. Data Acquisition. A wide variety of computer-based data acquisition systems (hardware and software) are now available off the shelf. They can be used to store inspection results in digital form (typically on hard or floppy disks). This data is then available for further data processing.

2. Housekeeping functions, including
   - (i) making test results independent of rope speed;
   - (ii) adjusting the distance indication on charts with reference to a location marker that is attached to the rope;
   - (iii) calibration of the LMA trace;
   - (iv) changing the offset of the LMA trace, if the inspection was started on a deteriorated section of the rope;
   - (v) repair and restoration of data that has been damaged by resetting the LMA and LF traces during an inspection (resetting might be necessary to prevent the traces of a stripchart from going off scale);
   - (vi) reversing the direction of the display in order to make test results compatible with previous test results that were acquired with the rope running in the opposite direction;
   - (vii) producing an overview chart showing the inspection results of the entire rope on one sheet. This will facilitate locating of critical rope sections.

3. Algorithms that extract additional information from the test results, such as
   - (i) high-pass, band pass and low-pass filtering of test results to distinguish between LMA that is caused by wear, corrosion and by broken wires;
   - (ii) miscellaneous data processing methods mostly for improving the resolution (or inspection accuracy) of test results.

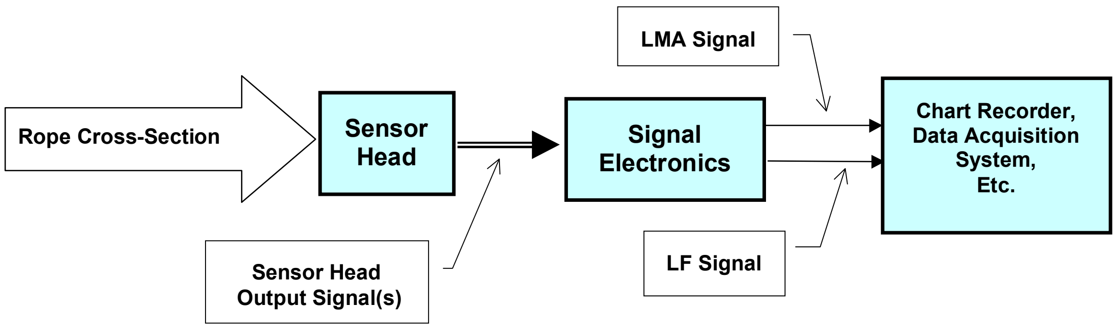
Items 1 and 2 above merely make chart evaluation and report writing more convenient. They usually do not contribute to the accuracy of chart interpretation.

Items 3, if implemented judiciously, can enhance and facilitate chart interpretation.

These algorithms together with the inherent signal generation and conditioning processes of EM rope testers will now be discussed.

3. Signal Generation

The *Functional Block Diagram* of Figure 1 illustrates the signal generation process. This figure shows the rope's cross-sectional area – including variations caused by broken wires, corrosion, abrasion, etc. – 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, which are then recorded by a chart recorder and/or stored by a data acquisition system.



<u>Figure 1</u>: Functional Block Diagram of the Signal Generation Process

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* has been called a *fundamental defect*. The corresponding LMA and LF signals, caused by a *fundamental defect*, are then called *fundamental LMA* or *LF signals*, respectively.

The *fundamental signals* could 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 superposition* are discussed further in (Weischedel 1990a). Determining and evaluating its *step response* is an excellent method for characterizing the performance of an EM wire rope tester.

Note that the concept of filtering can be – and frequently is – 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 2. 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 (like the LMA-Test™ instruments from NDT Technologies, Inc.), 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 2. (Note however that, compared to the *LF Signal*, the *Alternative LF Signal* appears more complex and more difficult to interpret.)

Recognizing differentiation as a 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.

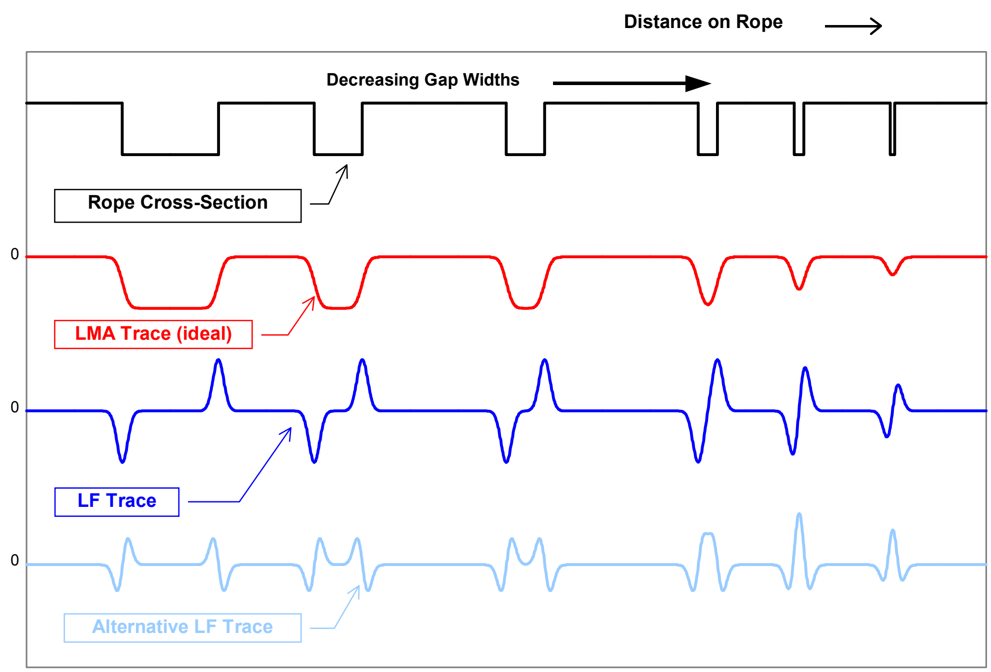


Figure 2: Input and Output Signals of an Idealized Rope Test Instrument

Most rope testers can produce LF signals with wave-shapes that are very similar to the idealized wave-shapes of Figure 2. However, producing an LMA signal that comes even close to the idealized LMA signal in Figure 2 poses considerable and almost insurmountable problems.

To illustrate, some EM rope testers produce *LMA step responses* with considerable overshoot in both directions similar to that shown in Figure 3. The overshoot makes LMA measurements complex, ambiguous and operator dependent. Chart interpretation for these instruments becomes especially problematic under actual field conditions. Because this type of performance is not amenable to analysis, it will not be discussed further.

Any computer algorithm 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. Unfortunately, actual LMA signals are far from this ideal. The rest of the present paper will deal with issues associated with the generation and conditioning of the all-important LMA signal.

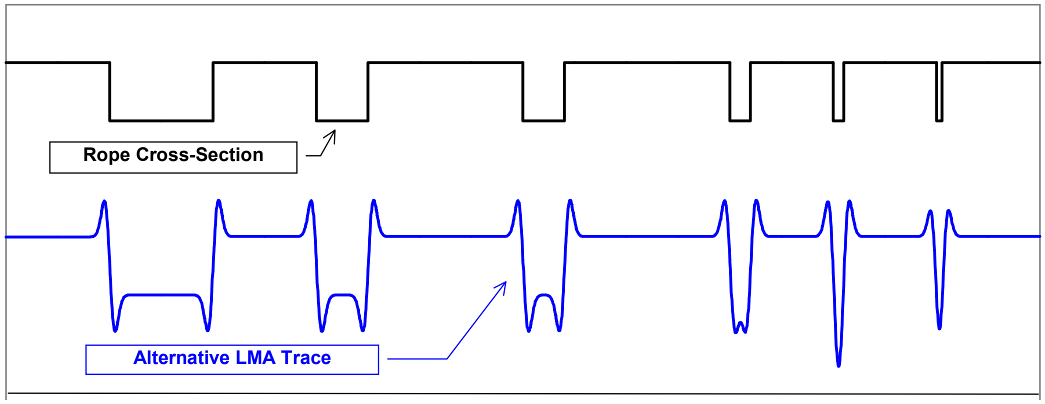


Figure 3: Alternative LMA Waveshape

4. Resolution and Averaging Length

The dictionary defines *resolution* as "*the fineness 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* (Weischedel, 1985) or *averaging length* (Poffenroth, 1989) (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 illustrate this concept.

Figure 4a shows a (hypothetical) rope with a uniform 10% LMA extending over a length of 300 mm. An instrument with a 300 mm *averaging length* will correctly measure this LMA. As illustrated by Figure 4b, a rope tester with an *averaging length* of 50 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 4d 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 4c, 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. The examples of Figure 4 show the importance of a short a*veraging length.*

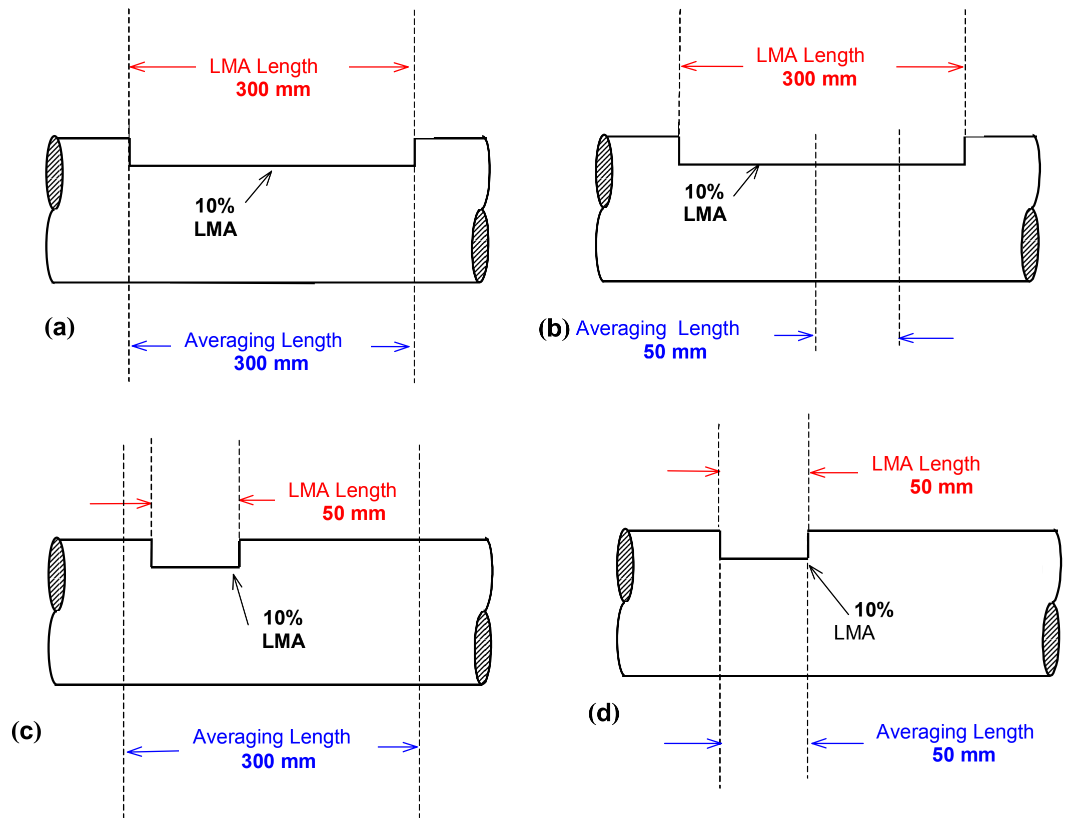


Figure 4: LMA Length and Averaging Length

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 LMA 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. The subject of *quantitative resolution* is discussed further in (Weischedel, 1998).

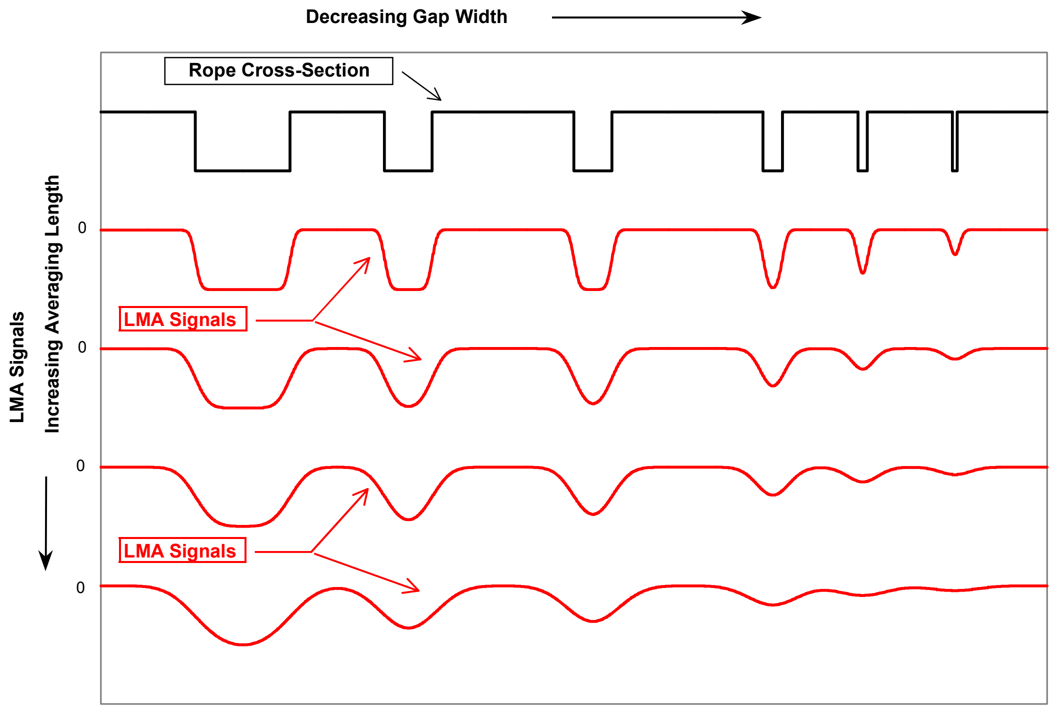


Figure 5: LMA Signals as a Function of Averaging Length

5. Miscellaneous Filtering and Signal Conditioning Methods

Recognizing LMA averaging as a low-pass filtering operation suggests immediately that some complementary high-pass filtering could mitigate this undesirable effect. For example, this scheme could be directly implemented by an electronic high-pass filter or by a computer-based high-pass filter algorithm. Alternatively, since the LF signal is approximately the derivative of the rope's cross-sectional area, the LF signal could be appropriately modified and added to the LMA signal to create, essentially, a high-pass filtered LMA signal. Again, this could be done by electronic circuitry or by a computer algorithm.

However, the practical implementation of this scheme poses some problems. For example, experience has shown that the performance is very sensitive to even slight variations of the filter parameters. Therefore, the design of such a high-pass filter is very difficult – if not impossible. If not designed with high accuracy, high-pass filtering can easily produce wave shapes that resemble the undesirable step response of Figure 3. Under all conditions, it is better to start out with an accurate LMA signal rather than trying to improve a mediocre signal after it has been generated.

Because it is hard to generate an accurate and easy-to-interpret LMA signal, and relatively easy to produce an adequate LF signal, attempts have been made to design methods for the quantitative interpretation of LF signals. However, this is an exercise in futility. Note that the LF signal is approximately the first or second derivative of the rope metallic cross-sectional area. Therefore, a quantitative evaluation of the rope condition with the LF signal is impossible (Weischedel, 1998). An analogy can elucidate the situation: The height of a mountain cannot be determined with an instrument that can only measure its slope.

The use of filtering can also be misused to embellish the general appearance of signals. For example, signals have been low-pass filtered to create a smooth impression and to simulate an improved signal-to-noise ratio. This scheme could be called *display cosmetics*. However, this procedure actually increases the averaging length, and improper low-pass filtering usually discards valuable information.

Readily available electronic circuitry, computers and small additions to sensor heads make various types of *display cosmetics* very easy. For example, they allow the generation of an infinite number of secondary signals from the basic LMA and LF signals. This capability has been commercially exploited by claiming to offer "more signals" – beyond the customary LMA and LF signals – than competitors. However, because these derived signals contain no additional information, they are frequently redundant and useless. Above all, they definitely cannot remedy the problems caused by deficiencies of the all-important LMA signal.

6. Instrumentation, Experimental Results and Signal Conditioning

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 this flux: Hall sensors and coils in combination with electronic integrator circuits.

To measure magnetic 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 flux inside the 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 axial rope flux from the external flux measurement.

Alternatively coils-cum-integrators can be used. Because coils must encircle the magnetic flux to be measured, coils can directly measure the magnetic flux inside the rope.

For example, Figure 6 shows an arrangement that uses an annular coil together with an electronic integrator circuit to determine the magnetic flux inside the rope. Originally patented in Britain in the 1960s (Whitehead, 1962), this approach has been discussed in the literature (Rieger, 1983), (Weischedel, 1985), (Weischedel, 1990b).

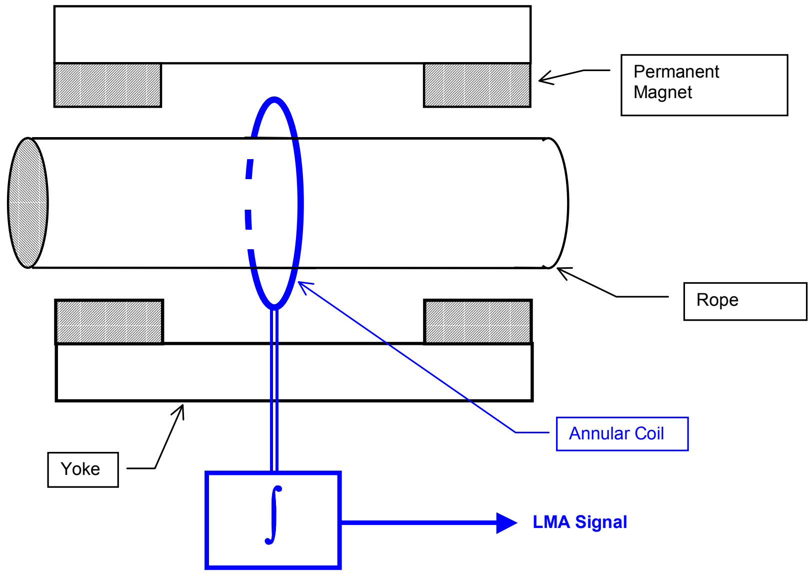


Figure 6: Annular Coil Method for LMA Measurement

To illustrate the *annular coil* approach, Figure 7 shows the LMA and LF traces of a laboratory test rope. The LMA and LF signals were acquired with an annular coil. Short pieces of wire that are 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 7 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. Therefore, the annular coil arrangement used for this experiment offers a *quantitative resolution* or *averaging length* of about 50 mm.

The above test results show that the *annular coil* approach offers uncommon resolution and signal fidelity. In fact, the averaging length (or quantitative resolution) of its LMA signal approaches that of the idealized LMA signal in Figure 2.

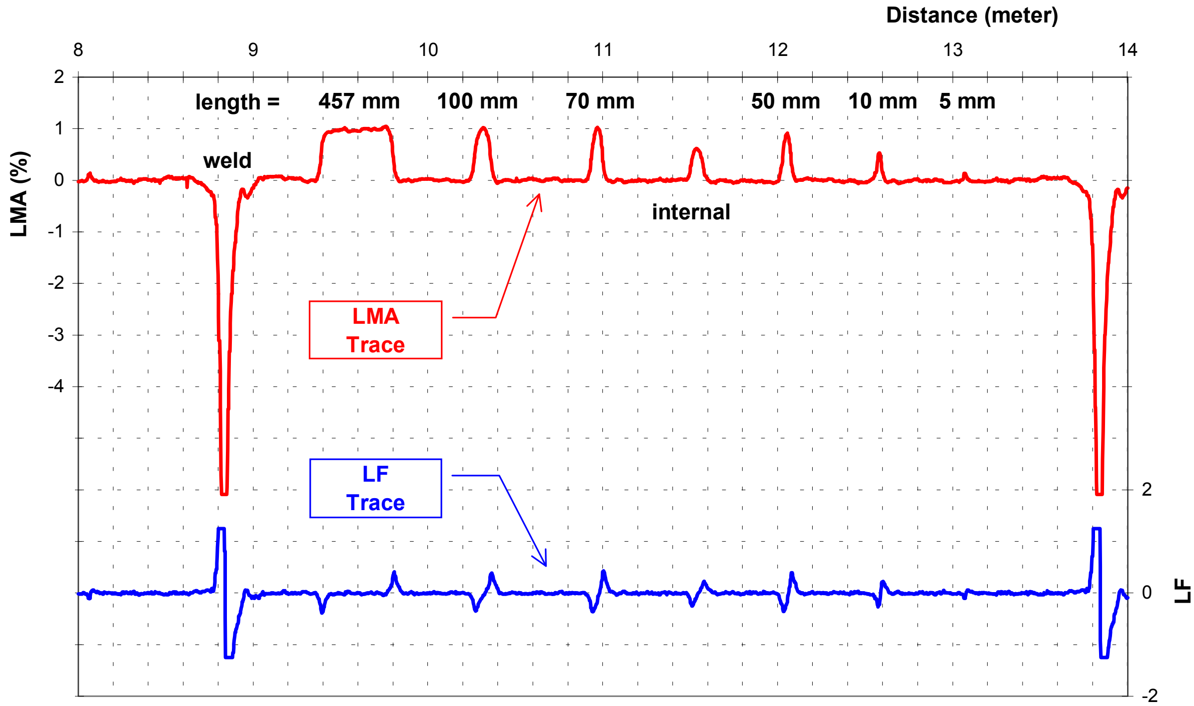


Figure 7: Step Responses for Annular Coil Method

In spite of its excellent performance, 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. Therefore, 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.

On the other hand, the annular coil approach is practical, if a coil with a large number – say, several thousand – of turns can be permanently installed on the rope under test. Then, the associated relatively high induced coil voltages make low-drift electronic integration possible. This approach has been implemented where continuous rope monitoring is desired.

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. To sidestep this problem the following approach was proposed (Weischedel, 1987), (Weischedel, 1990b).

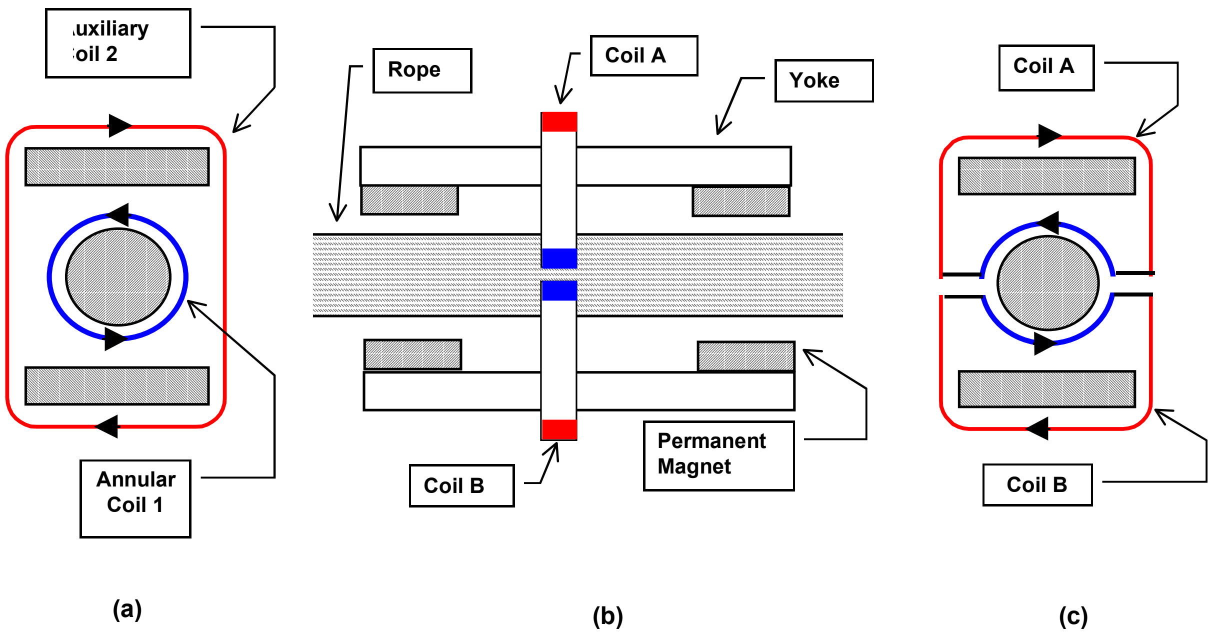


Figure 8: Auxiliary Coil Method for LMA Measurement

Consider the arrangement of Figure 8. Here, in addition to the *Annular Coil 1* in Figure 6, *Auxiliary Coil 2*, encircling the sensor head, was added. Assuming that the entire magnetic flux in the rope returns through the two yokes, the net flux encircled by *Auxiliary Coil 2* is zero, and no voltage is induced in the *auxiliary coil*. The two coils can now be subdivided and reconnected as *Coils A* and *B* (see Figure 8c). If the voltage in *Auxiliary Coil 2* is assumed to be identical to zero at all times, it is easy to see that the combined voltages induced in *Coils A* and *B* are equal to the voltage that is induced in *Annular Coil 1*.

The major advantage of this *auxiliary coil* method is the fact that it allows the implementation of hinged sensor heads of the familiar *clamshell* design. Also note that it is now possible to wind *Coils A* and *B* with several thousand turns. This makes the induced coil voltages sufficiently large to allow stable and accurate integration over long time periods of, say, an hour or longer. However, to achieve this performance it is still necessary to design and build a highly accurate and stable electronic integrator circuit, which requires some skill and experience.

Unfortunately, the above idealized assumptions are not completely correct. Comparing the experimental results of Figures 7 and 9, it becomes clear that the induced voltage in *Auxiliary Coil 2* is not equal to zero.

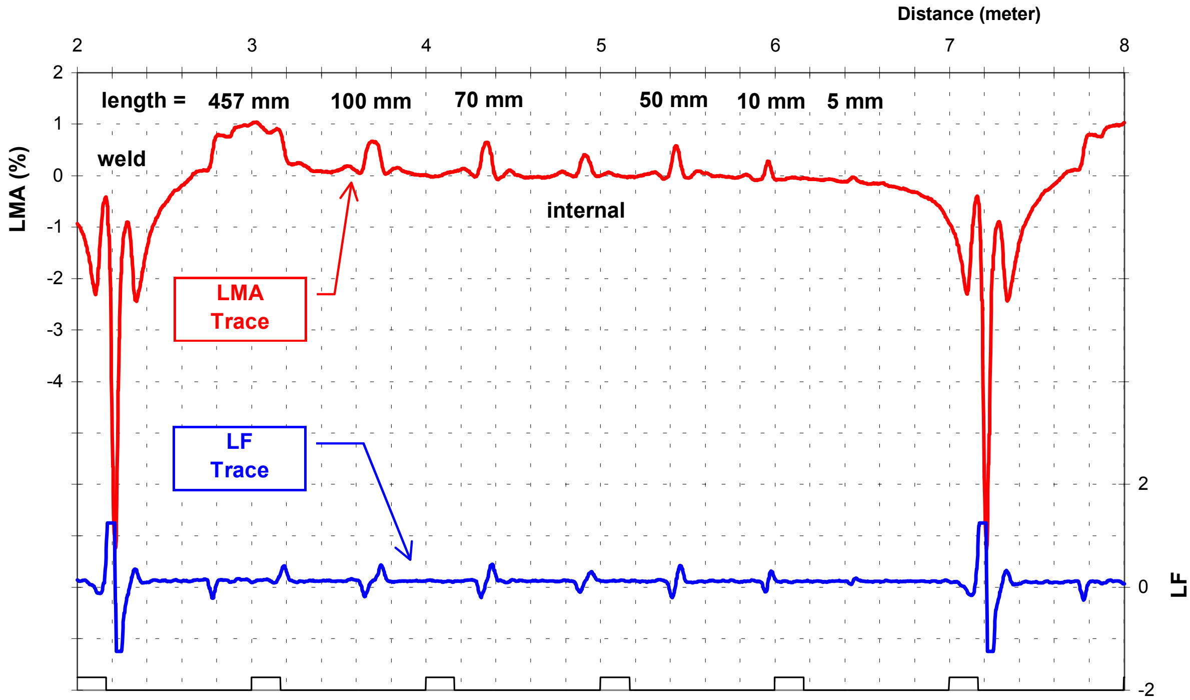


Figure 9: Step Responses for Auxiliary Coil Method

Nevertheless, the *auxiliary coil* method retains some of the desirable properties of the *annular coil* approach. For example, just like the *annular coil* LMA signal in Figure 7, the *auxiliary coil* LMA signal in Figure 9 still indicates very short attached wires. This means that the *resolution* or *inspection accuracy* – as defined above – is excellent for both LMA signals. Note, however, that the *averaging length* of the *annular coil* LMA signal is superior to that of the *auxiliary coil* LMA signal.

Compared to the LMA signal of the *annular coil* approach (shown in Figure 7), the LMA signal of the *auxiliary coil* method in Figure 9 is convoluted. This convolution is inevitable, if the hinged *clamshell* design (see Figure 8) is used. Note that the convolution is not caused by LMA averaging, and that it is possible to – approximately – de-convolute the LMA signal of Figure 9 by using the computerized *signal enhancement* algorithm described in the following.

Scrutiny of the Figures 7 and 9 shows the following approximate relationship between the two test results

$$f(z) = g(z) + \alpha[g(z+\delta) + g(z-\delta)], \qquad (1)$$

where z is the distance along the length of the rope, 2δ is the length of the sensor head, $\alpha < 1$ is an empirical factor (typically: $\alpha = 0.25$), g(z) is the LMA signal obtained with an annular coil shown in Figure 7, and f(z) is the LMA signal obtained with the coil arrangement of Figure 8. The term $\alpha[g(z+\delta) + g(z-\delta)]$ represents the additional voltages induced by *Auxiliary Coil 2* of Figure 8. Equation (1) could also be derived by considering the underlying physics of the arrangement of Figure 8. However, a discussion of this is beyond the scope of the present paper.

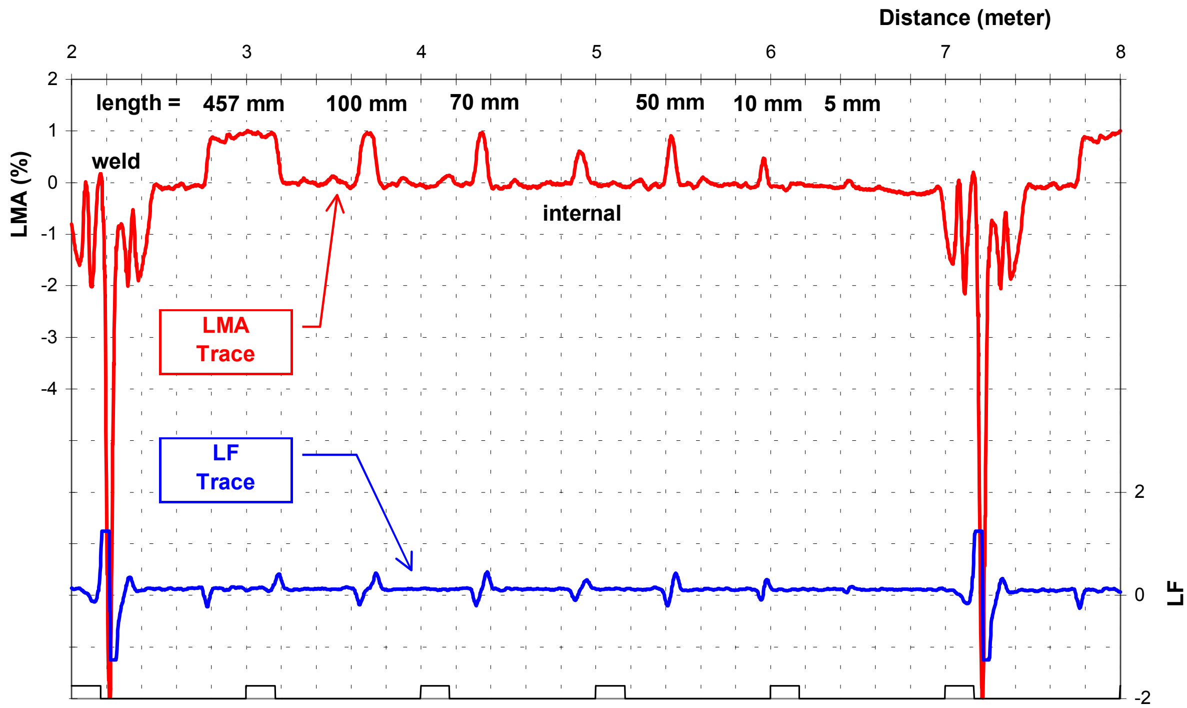


Figure 10: Step Responses for Auxiliary Coil Method
After Signal Enhancement

To extract the – highly desirable – *annular coil* signal (as shown in Figure 7), it would be necessary to find an explicit solution of (1) for g(z). This is not possible. However, an approximate solution can be found as follows: From (1), we have

$$f(z) - \alpha[f(z+\delta) + f(z-\delta)] = g(z) - \alpha^2[g(z+2\delta) + 2g(z) + g(z-2\delta)]. \qquad (2)$$

Since $\alpha < 1$, $\alpha^2 \ll 1$, and the second term on right side of (2) is small and can be neglected. This allows the approximation:

$$g(z) \approx f(z) - \alpha[f(z+\delta) + f(z-\delta)]. \qquad (3)$$

Equation (3) is called the *Signal Enhancement* Algorithm. It can be easily implemented on a digital computer. *Signal enhancement* is illustrated by Figures 9 and 10. Figure 9 shows the LMA trace – before *signal enhancement* – of a laboratory test rope that was acquired with a sensor head of the *auxiliary coil* type shown in Figure 8. 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 10 shows that, after enhancement (with the *Enhancement Algorithm* (3)), 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, as illustrated by Figure 7.

The effectiveness of the *signal enhancement* algorithm was only demonstrated for *step changes* of a rope's cross-section and the corresponding *step responses*. However, as discussed previously, the signal generation process as well as the signal enhancement algorithm (3) are linear, which, in turn, makes the combination of both operations linear. One important implication of linearity is that the response of an instrument to defects of any arbitrary shape can be determined from its *step response* by *linear superposition*. Hence, it is sufficient to show the effectiveness of *signal enhancement* for *step changes* of the rope cross-section and their corresponding *step responses*. For a further discussion of *linearity* and *linear superposition* see (Weischedel, 1990a). Note that the effectiveness of *signal enhancement* was also experimentally verified for LMA with a wide variety of geometries. A presentation of these experimental results is beyond the scope of the present paper.

The performance of the *annular coil* approach (Figure 6) is still significantly better than that of the *auxiliary coil* method (Figure 8), even after *signal enhancement*. For example, the *signal enhancement* algorithm (3) produces only an approximation of the *annular coil* signal g(z) from the *auxiliary coil* signal f(z). Furthermore, foreign moving steel objects in the vicinity of the sensor head do not influence the *annular coil* signals. This is not true for the *auxiliary coil* signals.

However, in spite of its shortcomings, it is believed that the *auxiliary coil* method, together with *signal enhancement*, offers the best overall performance that can presently be achieved with a divided and hinged sensor head of the *clamshell* design.

7. Summary and Conclusion

Wire rope test instrumentation should present data in a form that facilitates their interpretation by the human operator. A perfect LMA signal could serve as such an accurate and conceptually simple map of a rope's LMA that can be easily interpreted. Unfortunately, actual LMA signals are far from perfect. This paper reviews issues associated with the generation and conditioning of the all-important LMA signal. Various methods for improving the LMA signal are also discussed.

For example, the *signal enhancement* method presented in this paper effectively improves the *quantitative resolution* (or *averaging length*) – and, hence, the reliability and accuracy – of electromagnetic wire rope inspections. It allows more economical and safe rope operation by, simultaneously, preventing premature rope retirement and dangerous rope operating conditions.

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