From *Materials Evaluation*, Vol. 72, No. 8, pp: 1019–1027.

Electromagnetic Inspection and Diagnostics of Steel Ropes: Technology, Effectiveness and Problems

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ABSTRACT

Electromagnetic inspection has been used for steel wire rope nondestructive testing (NDT) for many decades. Today, this NDT area is rather wide and significant. The inspection technology varies widely as rope constructions and functions in different applications vary too. The state-of-the-art technology is based on modern materials, electronics, microcomputers, computer simulation of electromagnetic field and loss of rope strength process. Standards and norms play an important role in regulating the technology application during the entire rope lifetime, as do the inspection personnel training and their skill. New challenges come from offshore mining, suspended bridges, construction, high voltage overhead transmission lines, oil and gas drilling and so forth. On the other hand, the experience accumulated by design and application of magnetic and electromagnetic rope flaw detectors enables them to meet the challenges. Requests for rope monitoring come from the oil and gas industry as well as from mining now. This creates a need to automate process identification and evaluation of the rather big data volumes gathered.

KEYWORDS: steel wire rope, electromagnetic NDT, MFL rope flaw detector, rope lifetime, NDT cost-effectiveness, rope condition diagnostics.

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Introduction

The history of electromagnetic steel rope testing dates back many decades (Weischedel, 1988). Many rope testing instruments have been created over that time. There are manifold devices on the market designed for various applications. The main advantages are: high testing efficiency of objects through air gaps or through protective coating, lubricant, grease and so forth; high inspection productivity due to high testing speed; high sensitivity to rope deterioration, not only on the rope surface, but also inside; minimal operator participation thanks to the full-range smart software used for processing and interpreting testing data.

All the types of ropes used in different systems have a safety factor. It is calculated according to the theory of rope strength, and its limits are established for the real rope operation condition and the safety category of an installation (machine, construction and so forth). However, the loss of rope strength because of wire discontinuities often is not considered.

The discard criteria for deteriorated rope are used to avoid the safety factor decreasing below the established limit. Special software was developed to identify the real decrease in the safety factor because of the rope flaw detected, based on one or more established standards. Using the software, one can determine the rope residual lifetime and define the next rope inspection time.

Principle of Operation and Instrumentation

The instruments for electromagnetic and magnetic steel rope nondestructive testing (NDT) are based on the general principle: detection and evaluation of changes in the distribution of magnetic flux created by a magnetization system in a rope under test. The changes occur because the rope part under test contains irregularities, like wire breaks or a section with corrosion or abrasive degradation.

Magnetic flux leakage arising close to the broken wire can be detected by a sensor as the changes of the magnetic flux around the rope (or through it) are caused by changes in the rope cross-section area. The magnetization system located in a magnetic head most often surrounds the rope under test.

Figure 1 shows a diagram of the magnetic head with permanent magnets. It consists of two halves that clasp the rope. The half-ring-shaped magnets are magnetized radially to create a magnetic flow along the rope. The flow is closed by a yoke outside the rope. The nonferrous liners protect the magnets and a sensor unit surrounding the rope. The yoke serves as a head case.

The section of rope under test is magnetized to get the usual magnetic saturation condition. This provides the best testing result repeatability as well as the highest sensitivity to outer and inner fractures (Sukhorukov, 2013). To do this, one should use rather powerful magnets or electromagnets. That is why the magnetic heads for the big diameter ropes are heavy and large.

The sensor signals are received by an electronic base unit where they are processed, displayed and stored. The unit can be located on a magnetic head; then, the instrument enables movement along the rope under test, collecting and storing testing data. There is a wide range of magnetic flux leakage testing (MFL) flaw detectors for steel ropes. Thus, they are used for testing round cross-section rope with diameters from 6 to 150 mm (Figure 2).

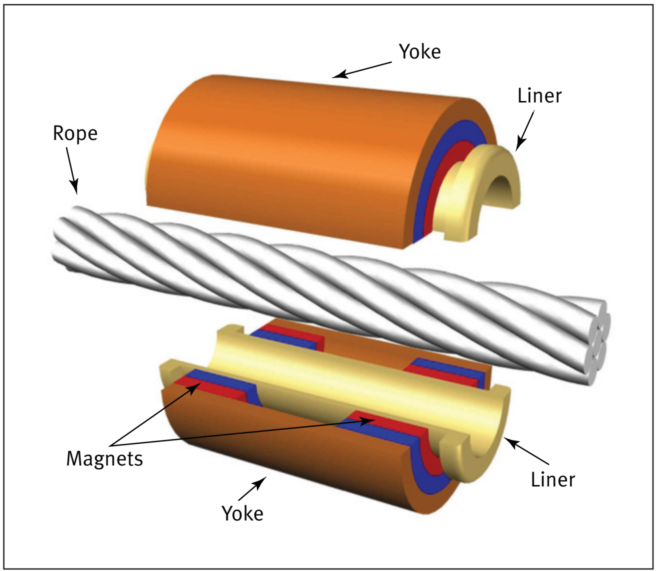

Figure 1. Diagram of a magnetic head for rope testing.

Practically, all MFL rope flaw detectors have two information channels: loss of metallic area (LMA) and local fault. The LMA value can be measured with an error no greater than 0.5 to 2% of the nominal cross-section area. The sensitivity limit of the local fault channel is one broken wire (out of more than 100) and depends on the break location: either on the rope surface or inside the rope.

Rope condition monitoring is a top priority in mining and oil and gas industries because of the strict requirements for safety, high cost of losses from accidents and significant loss from premature rope discard. It is possible to monitor ropes by ordinary MFL flaw detectors (Sukhorukov et al., 2003). In this case, testing frequency is increased considerably but testing is based on a usual routine procedure. To decrease time loss for testing, simplify the procedure and refine the skill of NDT inspectors, a rope monitor was designed for calf line of a drilling rig testing. Its features included: rugged design, high usability, simple rope condition indication (signal light), and storage of all the testing data.

The instrument's magnetic head was installed on the rope under test close to a winch drum, and the basic unit was located in the drill operator's compartment, as shown in Figure 3.

When the signal light on the basic unit indicator was red (or yellow), the operator would stop the winch and call a rope inspector to check the rope condition. The green light allowed work to continue.

The head could be set on or taken off the rope at any point.

Sophisticated software was designed for inspection data processing to automatically make a decision on rope condition and store data.

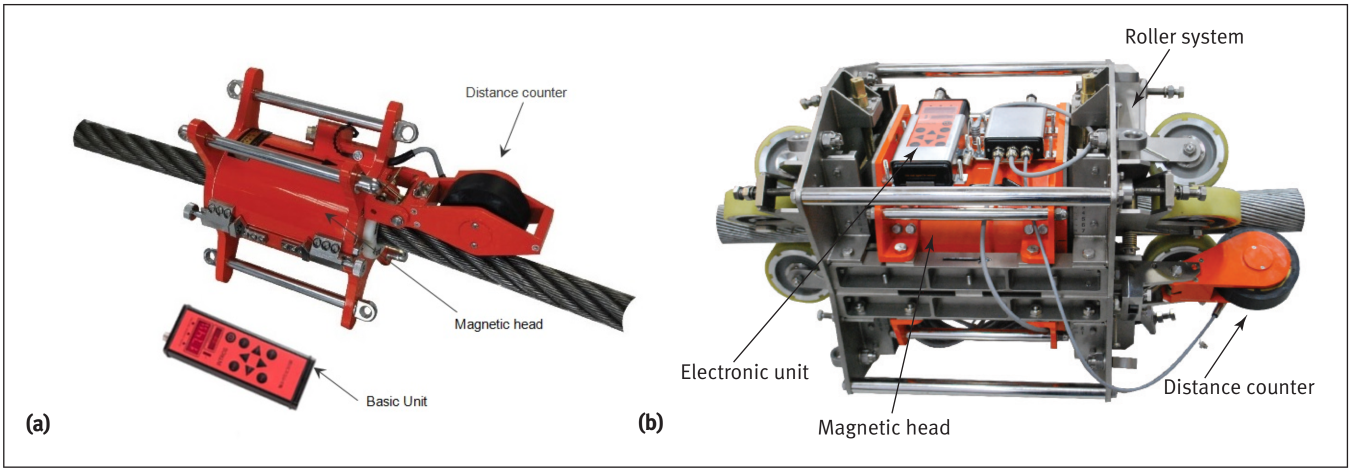

Figure 2. Magnetic flux leakage testing flaw detector design for rope diameter: (a) 20 to 40 mm; and (b) 80 to 120 mm.

(a)

(b)

(c)

Figure 3. Rope condition monitoring: (a) drilling rig with calf line under test; (b) the magnetic head on the rope; and (c) the electronic unit in the drilling operator compartment.

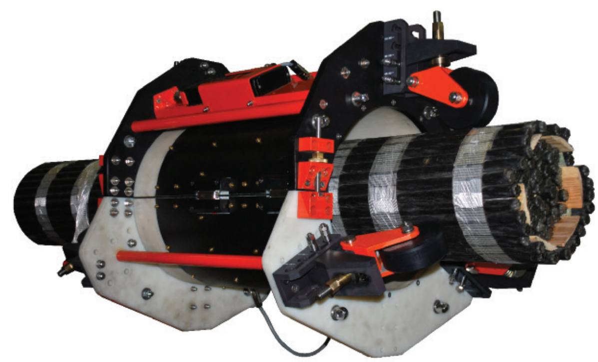

Figure 4. The electromagnetic head for testing rope diameter 150 to 300 mm.

All of the aforementioned steel rope flaw detectors are based on the MFL operation principle; however, its use for testing ropes with diameter more than 150 mm leads to the design of overly heavy and large devices. At the same time, inspection of such ropes proves to be rather important (Bergamini, 2008). The problem investigation shows that the electromagnetic operating principle could be used in this case. An encircling winding with an alternating current excites the magnetic field along a rope section under test. The rope serves as a very long magnetic core here, so an outer yoke is not necessary, making it possible to design a rather light testing head. Figure 4 shows the head for testing ropes with a diameter up to 300 mm placed on a 280 mm diameter strand rope simulator.

As the rope under test is not magnetically saturated, the metrological parameters of the device are worse than some MFL instruments. Thus, the limit of sensitivity in the local fault channel is several times worse than with the MFL instrument for rope diameter (100 to 150 mm), but the weight is reduced by more than half (Sukhorukov et al., 2012).

Rope Discard Criteria

Wire rope discard criteria belong to the following main groups. First, one can refer to the empiric fatigue regression model, which defines the ultimate number of tension /bending cycles as a function of operating parameters (Feyrer, 2007). Relations of this kind may be used for fatigue life prediction of a rope at a lifting machine design stage, but they are of a little use in practice because of the amount of factors acting on the rope endurance in real duty.

The second group includes the rope removal standards related to the limit values of typical flaws, most often to limit the number of wire breaks on a reference rope length (ASME, 2011; ISO, 2010). Similar criteria are used if any online diagnostic information is available about the individual rope damage during actual operation (Kashyap et al., 2005).

Lengthy and local flaws measured by the MFL method also decrease the rope loading capacity. The NDT data correlate with the endurance of degraded rope, but do not indicate its strength in a quantitative sense. The issue is that standard discard criteria based on an ultimate number of faults do not account for the combined action of various discontinuities on a rope's strength. Furthermore, LMA and local fault rates may differ significantly so it is hard to predict the lifetime of a rope and make a decision on its discard by these two wear characteristics.

A new way of looking at the wire rope discard problem is that the diagnostic indicators – LMA and local fault – should be considered as input data for the pertinent rope's mechanical model (Vorontsov et al., 2007). This model enables one to obtain a generalized parameter, for example, the safety factor that specifies the rope's mechanical condition varying over time. A safety factor value correlated with the conventional empirical discard requirements may be chosen as an allowable strength limit for deteriorated rope.

Rope manufacturers strongly discourage the use of wire ropes for cranes handling hot metal at temperatures above 723 K (450 °C). So far there are no quantitative safety criteria for steel ropes in hot working conditions. For this reason a two-parametric thermal safety criterion was developed for predicting the rope state in a high temperature environment at steel mills (Vorontsov et al., 2013). The operating pattern is formulated in two variables: the temperature of outer wires and the number of thermocycles (hot metal ladling). Because of general uncertainties of thermal regimes and of the wires' magnetic and mechanical properties, the criterion has a peculiar "caution" buffer zone that separates the acceptable and unacceptable working conditions. The limit discard border relates to situations when the specified rope diagnostic variable begins to grow dramatically.

The proposed interval criterion was applied to set the magnetic testing schedule of ladle crane ropes at a metallurgical plant in the Russian Federation.

Testing Practice, Personnel and Cost-effectiveness

Steel rope testing by magnetic and electromagnetic instruments is the only practical NDT method for this currently. Of course, it is done in close combination with visual testing. Rich experience of its use over a long time has resulted in rules and norms, both national and international. For example, *ASTM E 1571-11* or Russian Federation norm *RD-03-348-00* establishes requirement calibration techniques, reference standards, testing results interpretation and so forth (ASTM, 2011; Gosgortechnadzor, 2000). Other groups of standards define testing procedures for ropes installed in concrete objects, for instance, in cranes (*ISO EN 4309*) and in aerial ropeways (*BS EN 12927-8*) (BS, 2004; ISO, 2004). But it is necessary to expand these requirements for electromagnetic NDT of crane ropes. Currently, rope NDT is compulsory only for detection of a rope's inner flaws. Rope surface deterioration, like LMA and broken wires, may be visually detected according to *ISO EN 4309*. Evidently, this is not true for stay ropes and ropes under lubricant and grease.

The most important requirements belong to the calibration techniques and testing result interpretation. Two types of reference standards are used for rope test calibration: rod or wire bundle standard (imitator) and rope standard. They are used not only for instrument calibration but also for operation testing and metrological parameter checking. Of course, some parameters depend on the rope under test's condition. Thus, the limit of sensitivity in the local fault channel, such as a broken wire with a minimal cross-section area, which can be detected by an instrument, depends on rope homogeneity. Rope inhomogeneity creates a noise at the sensor output and decreases the signal-to-noise ratio. That is why the limit of sensitivity to broken wire is defined by the use of reference standards. Their parameters (structure, dimensions, magnetic permeability, homogeneity) can be checked when it is necessary.

Besides the norms mentioned earlier, there are specific recommendations and instructions created by companies producing and using the rope testers, for example, procedures for rope testing of different types of cranes, for fixed and moving ropes of ropeways, for bridge stay ropes and so forth.

Testing conditions of crane ropes are various. It is very important to define a proper location of the rope tester, which must be easy to use and provide testing of the maximum accessible rope part.

Figure 5 illustrates an example of big crane (stacker) rope testing.

Rope inspection of ropeways is another wide application area of magnetic rope testers. Sometimes it is necessary to test not only moving ropes but also fixed ones such as bridge stays or suspension ropes. The testing head is moved along the rope by hand or by winch pulling, as shown in Figure 6. When the stay ropes are positioned too close each other, a custom modified testing head is used.

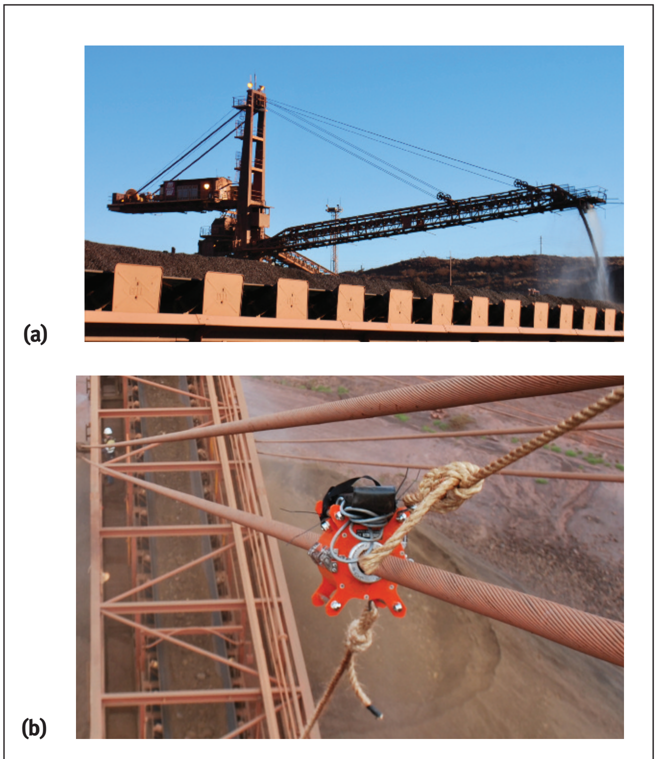

Figure 5. Rope testing in Paraburdoo, Australia: (a) the commercial stacker being tested; and (b) magnetic head on the rope.

Figure 6. Stay rope testing at the Yeongjong Bridge, South Korea.

The successful use of the rope tester depends dramatically on operating personnel. Norms and rules have established requirements for rope testing technicians. There are two levels of rope testing operator in Russia, for example. The levels are differentiated by their skill: the first level operator may use an instrument for rope testing according to instructions, and the second level operator may do this too, as well as interpret test data and make a decision on rope condition and its discard. The program of personnel training is conformed to the National Safety Supervising Body on Technology (Gosgortechnadzor).

Understandably, the main aspect of steel rope NDT is safety against potentially dangerous objects and conditions, but the cost of safety is rather significant. Even if one does not take into account losses from object accidents because of a rope break, the loss of money because of untimely rope discard is considerable. The following example from the Russian mining industry illustrates this.

Approximately $130 000 was saved by a mining company through lifetime prolongation of ropes, which must be discarded according to the lifetime limit criteria. The prolongation was based on testing results obtained by rope NDT using MFL flaw detectors from 1995 to 1999. Besides that, approximately $1 000 000 was made in profits over five years due to:

- an increase of useful working time of a hoist due to reduction of inspection time;
- decreased expenses for the cutting off of rope samples and their destructive testing;
- saving of funds by not having to change ropes when they became too short because of cutting samples off (Sukhorukov et al., 2003).

Testing Data Processing and Displaying

Informative data, acquired from magnetic measurement systems, are typically divided into two traces – LMA and local faults (Gronau et al., 2000). The first corresponds physically to the absolute sensor channel and the second to the differential sensor channel. The LMA trace signal is inversely proportional to the metallic cross-section of the rope. The local fault trace signal stays in some relation to the size of the fault. Signals of these traces are subject to different influence factors, of which the main factor is an inhomogeneity of magnetic properties and mechanical structure of the rope. As a consequence of this, LMA and local fault signals are subject to some stochastic (noise) and non-stochastic disturbances. Therefore, both traces should be processed by special algorithms to reduce the influence of these disturbances on the result trace interpretation. Moreover, advanced signal processing algorithms enable automatic flaw detection, which reduces time of trace analysis.

Typical processing of an LMA trace assumes noise reduction by means of a low-pass filter. It allows for the suppression of noise, caused by rope movement in a magnetic head and by the local variation of material magnetic properties and the rope geometry. This filter also reduces transient noise caused by the magnetic measuring system and, thus, removes distortion of signal magnitude for short discontinuities. It should be noted that correct processing does not significantly reduce spatial resolution of an LMA trace. Figure 7 shows the result of LMA trace processing with a low-pass filter (red) against unprocessed LMA (blue) for a 39.5 mm rope sample. It can be seen that an LMA estimation error of approximately 1% takes place only for discontinuities with a length of 100 mm, and so LMA spatial resolution is approximately 100 mm, which is less than 3 rope diameters. Additionally, for short discontinuities, the LMA signal magnitude decreases simultaneously with a decrease of the gap between broken wire ends; this is important for correct trace interpretation. The appropriate cutoff frequency can be unambiguously calculated on the basis of sensor impulse response.

Processing of the local fault trace depends on the type of sensor and on the construction of the rope. The main purpose of local fault trace processing is to increase sensibility to wire breaks by suppressing different kinds of disturbances. Special filters are applied to achieve this. For example, in many cases the raw local fault trace is subject to disturbance from the strand structure of the rope. This can be noticeably reduced by an appropriate band-stop filter, which suppresses a strand component.

Proper signal processing and chart representation possibilities can help experts analyze results of rope NDT. Nevertheless, analysis of long rope charts is rather tiresome work and can entail subjective errors. Correct analysis also presupposes high expert qualification. Automation of data processing allows for reducing time expenses for results interpretation and requirements for expert qualification. This, first of all,

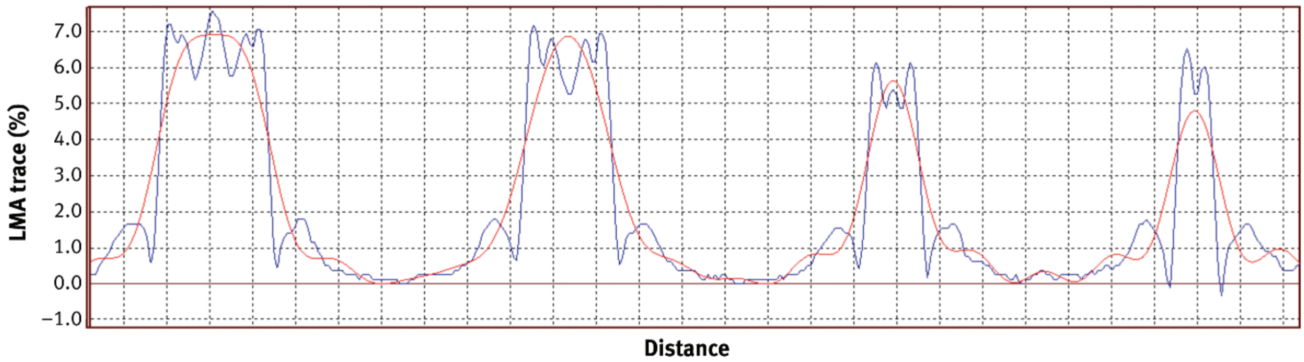

Figure 7. Loss of metallic area (LMA) trace before and after filtering.

means automatic detection of localized faults (wire breaks) and identification of rope sections with a critical LMA value, concluding with the checking of rope discard criteria. The results of automatic trace processing are normally viewed and, if necessary, corrected by an expert. Automatic trace processing enables preparation of data for the calculation of residual load-carrying capacity (Slesarev et al., 2012).

The next promising step in rope NDT is a regular automatic rope condition estimation or continuous rope monitoring (see Figure 3). It assumes daily rope inspection and estimation of a rope's technical condition. It makes some challenges to the design of the diagnostic system, which should be robust enough for permanent installation on the rope and realizes reliable automatic processing of inspection data. In this connection it is important to remember that automatic rope condition estimation has a probabilistic nature, so the final decision should be made by an expert.

Rope Condition Diagnostics and Rope Remaining Lifetime Prediction

The working rope condition may be simulated by an appropriate mechanical model (Costello, 1997). The rope is treated as a two-degrees of freedom system with constitutive equations derived from the kirchhoff thin bar theory. Mechanical state relationships of straight rope connect a tensile force, T, and torque, M, with generalized axial deformations of the rope – the relative elongation, ε, and relative angle of twist, θ.

(1) $$\left.\begin{array}{l} T = C_{11}\varepsilon + C_{12}\theta \\ M = C_{12}\varepsilon + C_{22}\theta \end{array}\right\}$$

The effective stiffness coefficients, C_{jk}, of the rope considered as a heterogeneous structure depend upon the wire stiffness and helixes geometry of wires and strands. For deteriorated rope they are evaluated with account to measured metallic cross-section loss and wire break locations. Expanded expressions for stiffness parameters, strains and stresses are rather complicated, so only the general strength assessment procedure is described here.

The rope deformations, ε and θ, are determined by Equation 1 for given loads, T and M, and known stiffness value, C_{jk}. These deformations are double-transformed to strand lay axes and wire lay axes. The tensile, bending and torsional strains and corresponding normal (σ) and shear (τ) stresses are evaluated in a helix coordinate system of each wire. The combined stress state in the most strained wire (weak component) is reduced to uniaxial equivalent stress, σ_{eq}, by proper strength criteria, for example, σ_{eq} =sqr(σ^2 + 4τ^2). The stress safety factor relative to the wire ultimate tensile strength, σ_u, is defined as follows.

(2) $$n_s = \frac{\sigma_u}{\sigma_{eq}}$$

When the wire ropes are subjected to fluctuating loading during their service life (for example, running over the sheaves and drums) the fatigue endurance should be taken into account (Vorontsov et al., 2011). In this case, the actual safe state of the structure is characterized by the minimal value of steady-loading safety factor, n_s, and of fatigue safety factor, n_f (Gere and Timoshenko, 1990).

(3) $$n = \min\left(n_s, n_f\right)$$

The rope strength at operating time, t, is qualified by the safety factor, $n(t)$. It is a minimal value of corresponding parameter, $n(x,t)$, which varies with coordinate x along the rope axis due to structural discontinuities.

(4) $$n(t) = \min_x n(x,t)$$

The duty state of the rope meets a condition.

$$n(t) \geq [n] \quad (5)$$

The allowable safety factor, $[n]$, defines the rope's margin of survivability as for a partially failed structure. It specifies a reasonable risk when operating the rope with worn-out elements and is called a vitality factor in the theory of reliability (Bolotin, 1989). It may be determined from rope lifetime experiments or estimated regarding the corresponding discard rules.

When Equation 5 does not hold, this signifies the rope's failure. The rope's near future depends upon answering three questions:

- Should the work of the rope stop or continue at the achieved operating time, t, factoring in recent inspection history?
- If the decision is to continue, at what operating time should the next examination be conducted, and what value for safety factor is then expected?
- What operating time does it leave for the rope just after the last inspection regarding the ultimate "vital" factor, $[n]$?

To answer these questions one should have a degraded rope safety factor history, which, in turn, is a sequence of NDT history. In the absence of individual rope failure statistics and prior probability assessments of service conditions, this study was restricted to deterministic lifetime prediction based on the least-squares extrapolation of the safety factor changing to the vital limit. The forecasting procedure was adjusted for degradation rate and proximity of safety factor, $n(t)$, to an ultimate value, $[n]$. The details of rope downgrading estimator are presented elsewhere (Vorontsov et al., 2007).

An example of using the NDT data for strength and lifetime assessment is demonstrated for cargo crane rope that has been operating under tension-bending fatigue loading. It was examined five times by a commercial magnetic flaw detector. The rope diameter was 8 mm, sheave diameter was 350 mm, nominal tension was 10 kN and tensile strength of wires was 2160 MPa. The number of loading cycles was considered as an operating time, t.

Any noticeable LMA was not detected. The wire breaks were only revealed after the third inspection. Processed local fault data were imported to the rope strength application, and corresponding distributions of strength estimates over the rope distance were evaluated. The third, fourth and fifth local fault charts along with the time-quantified safety parameter, $n(x,t)$, are shown in Figure 8.

Local faults indicate the interval where rope failures develop and will probably occur. The minimum values (marked by circles) may be treated as the operational factors of safety, $n(t)$, and adopted as implicit discard parameters of deteriorated rope. They also serve as rope state indicators for planning the dates of next inspections and for predicting the remaining lifetime.

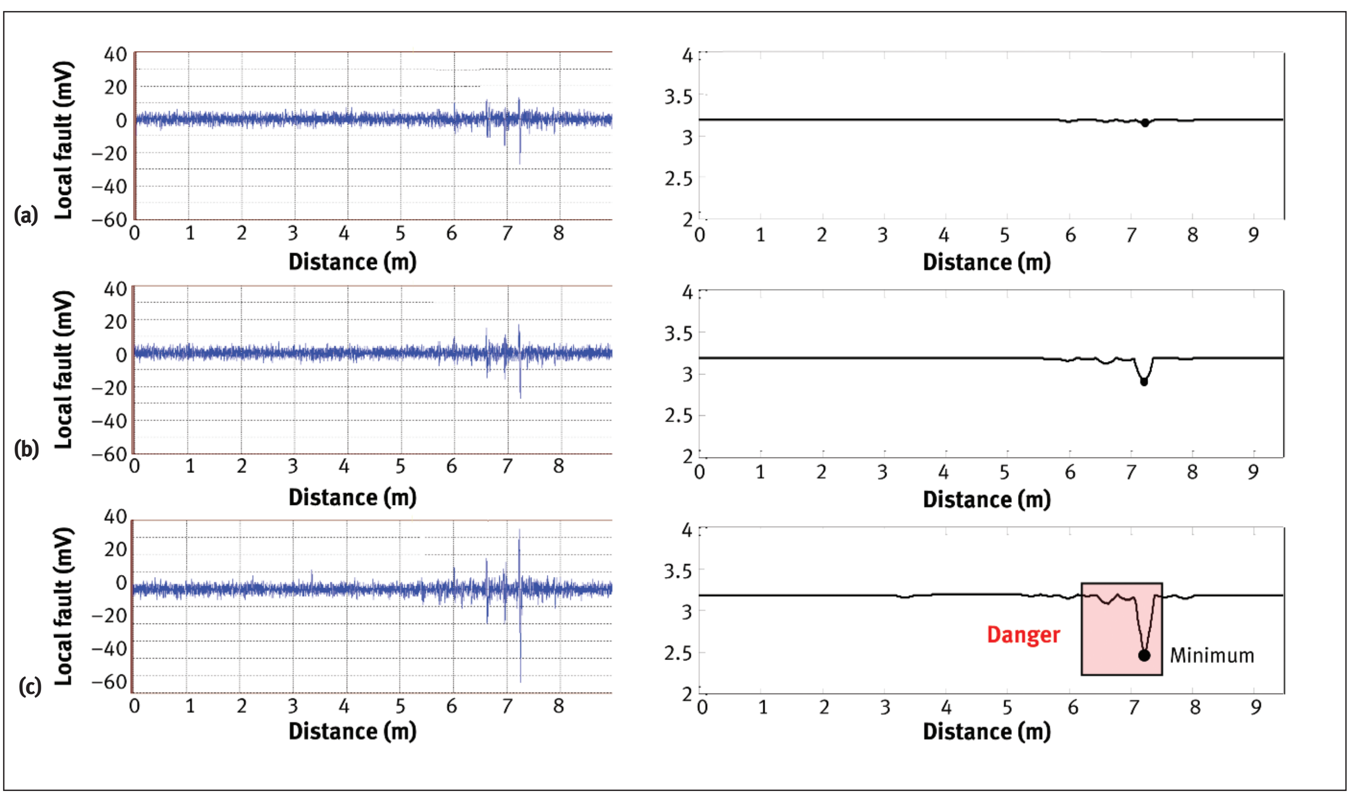

Figure 8. Local fault charts and distributions of crane rope strength parameter: (a) in June 2007; (b) in October 2007; and (c) in November 2007.

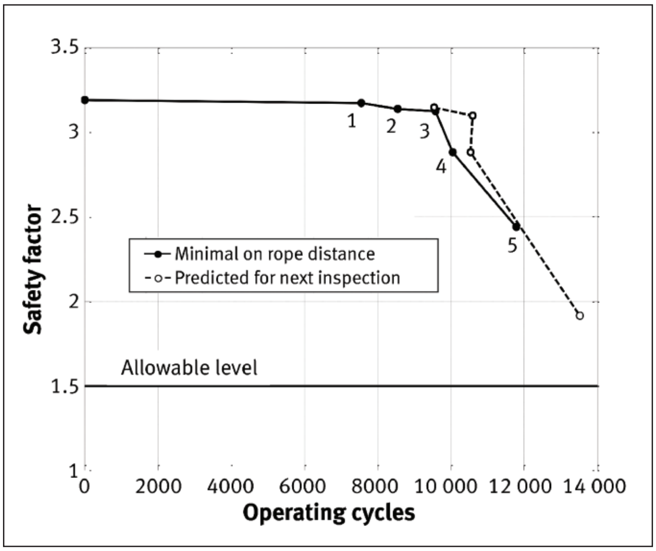

Figure 9. Safety factors and prospective estimates for crane rope.

Figure 9 presents the changes in both the safety factors, $n(t)$, and expected values for planned inspections for all NDT history of the rope. The new rope at delivery had a safety factor of 3.2. The allowable level, $[n] = 1.5$, was evaluated with respect to normative local fault standards for rope type under examination. The final planned quantity of operating cycles to the next inspection was equal 13 508 with an expected safety factor of 1.91.

The remaining lifetime tendency of progressively degraded rope is presented in Figure 10. Wire discontinuities accumulated within 6.3 to 7.5 m segments provoke a significant

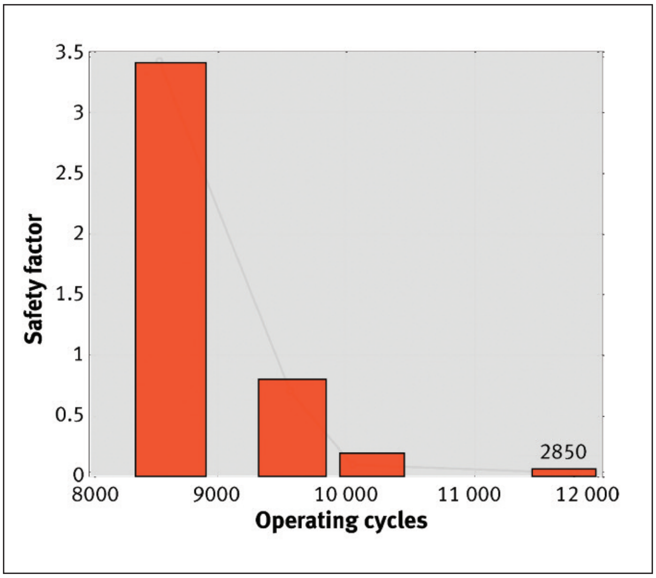

Figure 10. Remaining lifetime estimates for crane rope.

fall of the expected rope's service duration. After the last inspection the rope could have reached a defined discard condition of 1.5 in 2850 operating cycles. That rope was not tested further by duty reasons and its real total operating time was unknown.

Theoretical predictions should be considered purely as suggestions for the hoisting engine maintenance staff to make the final decision upon the technical state of the rope and what future actions should be undertaken. Nonetheless, periodic NDT combined with strength modeling permits the revealing of future potential accidents.

Problems and Solutions

New problems in steel rope testing are connected with several tendencies: on the one hand, it is a general tendency of automated continuous condition monitoring; on the other hand, testing of ropes in unconventional conditions, for example, underwater mooring cables or testing of big diameter ropes of cable-stayed structures. These new problems present challenges for diagnostic instruments.

As written earlier, continuous rope monitoring creates several special conditions for the testing instrument. This results in particular requirements for the construction and operating principles of the equipment. Specifically, this means exclusion of regular calibration operations and low variability of instrument characteristics in a wide range of influence factors. Data processing algorithms should recalculate measurement traces into some equivalent values, which can be compared with rope discard criteria. One typical discard criterion is critical LMA value, which can be measured directly. The other criterion concerns the amount of local wire breaks at some determent rope length (*ISO 4309:2010*) and should be estimated indirectly (ISO, 2010). One possible estimation can be based on certain cumulative values obtained from LMA/local fault traces, for example, wire rope roughness, which should be proven to relate to real density of wire breaks (which is not obvious) (Weischedel, 2013). Another way to estimate density of wire breaks is based on wire break automatic detection via local fault trace, which presumes high spatial local fault resolution and a noise-proof detection algorithm. Such an approach was realized in the automated monitoring system for the calf line of a drilling rig (Figure 3). In any case, it is important to keep in mind that the decision to discard the rope should be made by responsible personnel and not by the system itself.

Some special cases concern the testing of underwater ropes. Obviously the instruments should have a waterproof version, but for depths of several hundred meters this means a thick protective shell. At the same time, one should take into account organic and inorganic sediments on the rope. Altogether this results in a considerable increase in the gap between the rope and the sensor, which leads to a reduction of local fault sensitivity and resolution. This challenge has yet to be addressed.

Another unconventional application of steel rope testing consists of the condition estimation of overhead line steel-aluminum conductors and steel earth wires. Deterioration of steel wire core leads to a loss of mechanical strength of the wire. It should be tested in regards to specific wear mechanisms and in the presence of the neighboring current conductors under the power. Some conventional instruments can be used but in the framework of new particular procedures.

All the aforementioned new applications need appropriate actualization of international standards and norms.

Conclusion

Electromagnetic inspection is currently the most widely used NDT method on steel wire ropes throughout the world. There are many different instruments for rope testing in diverse areas of industry, construction and transportation. These instruments have good metrological parameters and make it possible to provide a high safety level of machines and installations with ropes as well as to save money because of their high cost-efficiency. Sophisticated software has been developed for diagnostics and prediction of rope lifetime using testing data. Standards and norms have established requirements for the instruments and their applications for operating personnel, but it is necessary to extend the use of rope NDT for such objects as drilling rigs, stay ropes and suspended bridges, excavators, high voltage overhead transmission lines, radio and television masts, gas flares and so on.

Electromagnetic technology for rope NDT progresses permanently and meets the challenges from new areas due to the use of contemporary achievements in physics, microprocessors, software, electronics and theoretical investigations.

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