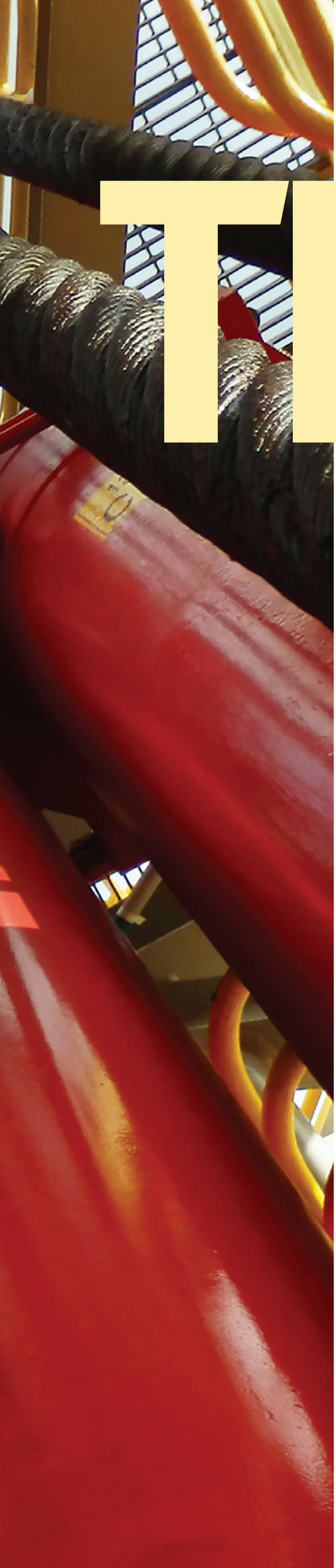
ROPE



TEST

Steel Rope Diagnostics by Magnetic NDT: From Defect Detection to Automated Condition Monitoring

by Vasily V. Sukhorukov

Today it is hard to imagine an industry or an application that uses steel wire ropes in which the application of a magnetic flaw detector would be unsuitable. The ropes of loading cranes, mine hoists, ropeways, cable-stayed bridges, flare stacks, antenna masts, overhead power transmission lines, and other installations are not only subject to regular inspections (Sukhorukov and Mironenko 2003; Kotelnikov and Sukhorukov 2006; Sukhorukov et al. 2014), but the appropriate guidelines for these rope types are now described in industrial standards such as the International Organization for Standardization (ISO) standard for crane ropes, ISO 4309 (ISO 2017); the European Standards (EN) standard for ropeways, EN 12927 (BSI 2019); and the International Marine Contractors Association (IMCA) standards for offshore ropes, IMCA LR 004, IMCA HSSE 023, and IMCA M 197 Rev.1 (IMCA 2018).

Current Challenges of Magnetic Rope Testing

Contemporary magnetic rope testing equipment is state of the art and very universal. The vast assortment of available products offers a range of approaches on how to induce and register magnetic flux leakage signals. As standards continue to push for greater accuracy and precision, manufacturers strive to make their equipment compliant.

This paper examines how MFL is used as the basis for an automated wire rope condition monitoring system, in which the human factor is completely removed.

Though rope testing technology will continue to improve, every inspection results in a report, the compilation of which will remain dependent on the qualification of the person writing it. Interpretation of magnetic rope testing traces not only requires great expertise and experience for each individual inspection, but is also very laborious when it comes to cross-referencing the results with previous ones.

Ultimately, the report decides the fate of the inspected rope. The Russian standard on technical diagnostics, GOST 20911-89 (Standartinform 2019), defines three conditions: operable, near-discard, and discard. In the case of magnetic rope testing, it can be increasingly difficult to distinguish between the latter two once the degradation passes the first threshold. Moreover, the rate of degradation will increase as the load-bearing capacity of the rope plummets due to the ever-growing number of broken wires.

Figure 1. A flaw detector's magnetic head after a single inspection of a crane rope in a metallurgical plant.

The only way to track this cascading effect is to decrease the inspection intervals, making the human factor issue ever more acute. While the primary costs of such NDT inspections can be rather high, the practical issues of maintaining such a service division will manifest in further economic burdens, particularly if the sites are located in very remote and/or hard-to-reach locations. If the accompanying costs are manageable, the losses due to the production cycle interruption of the machinery on standby while the inspection takes place are not.

In extreme cases, many operating companies may choose to circumvent rope testing altogether and mitigate the accompanying risk factors by shortening the rope replacement schedule. The reality is that these increases in operational costs may be less than the gross rope inspection expenditures and the potential savings they bring.

It is an understatement to say that these challenges are not foreseen. Luckily, the capabilities of contemporary computing allow us to refine rope testing technology in new ways. This paper examines how magnetic flux leakage testing (MFL) is used as the basis for an automated wire rope condition monitoring system, in which the human factor is completely removed.

From Periodic Inspection to Continuous Monitoring

The main criterion for discarding a worn rope is the loss of metallic cross-sectional area (LMA) caused by abrasive wear and the presence of local faults (LFs), such as wire breaks per a defined rope length (6D or 30D, where D refers to the rope diameter). This criterion is fixed in international standards (such as

ISO 4309:2017 and EN 12927) and many national norms (such as RD 03-348-00 from the Russian Federation [2017] and SANS 10369 from South Africa [SABS 2007]).

Attempts to systematize the tracking of rope wear and record its deterioration using discrete MFL data sets have been made repeatedly. The earliest one was focused on mining hoist ropes at the Norilsk Nickel Co. in Russia from the end of the 1990s to the early 2000s (Sukhorukov and Mironenko 2003). Data was collected every few months or a few tens of thousands of operating cycles apart. Despite the limitations, it was possible to follow the dynamics of rope deterioration. Similar approaches have been carried out at mine hoists in Germany (Gronau et al. 2000) and in South Africa (Marias and Bester 2011).

In 2010, data sets from MFL rope testing were collected from 53 drilling rig calf lines (Slesarev et al. 2014). The results showed that 13 of these lines were not suitable for further operation, in spite of them not exceeding the respooling period. From this work, a set of operating guidelines was published that set inspection periods.

These results drew interest from the drilling companies, but it was clear that periodic MFL rope testing using regular instruments was unsuitable for calf lines as the challenges described previously came to the forefront. Working closely to requirements, the specifications arose for a system that would automate the interpretation and analysis process.

The project started with the integration of a standard flaw detector design. The magnetic head that encircles the rope and magnetizes it to record the magnetic flux leakage had to be made more robust and wearproof. Figure 1 illustrates this requirement, showing how a standard magnetic flaw detector was used for a single inspection of a crane hoisting rope in a metallurgical foundry.

As seen in Figure 1, the amassed coating of graphite dust on the rope mixes with the ferromagnetic particles caused by the abrasive wear of the rope. Regular NDT in such conditions will inevitably lead to damage of the protective liners inside the instrument's magnetic head and from there, its internal sensors and circuitry. Despite the robust nature of flaw detectors, their suitability for continuous operation in such environments is limited.

Flaw detector designs require physical contact with the rope under test due to the limited area of magnetic flux leakage caused by LMA or LF. A disposable plastic or bronze liner was thus the only medium protecting the magnetic head from damage. More modern sensor units, typically a combination of Hall sensors and induction coils, can register the rope's condition at a much greater gap, allowing for a noncontact interface.

Figure 2 illustrates two design concepts of a magnetic head built for monitoring. Figure 2a shows a design suitable for the periodic monitoring of a drilling rig calf line. The two pairs of guide rollers prevent contact with the rope's surface, yet allow the magnetic head to follow the horizontal travel of the rope along the drum, while the handles and locks make its removal from the rope easy. Figure 2b shows a design for more permanent installations, such as for hot-metal crane ropes. The larger orifice accounts for the expected rope oscillations and vibrations. The latter unit was ultimately installed on the crane rope that caused such damage to the standard flaw detector depicted in Figure 1.

(a)

(b)

Figure 2. Two designs of a magnetic head for an automated condition monitoring system: (a) design for periodic monitoring of a drilling rig calf line; (b) design for more permanent installations, such as hot-metal crane ropes.

(a)

(b)

(c)

Figure 3. A typical drilling rig installation: (a) drilling rig on job site; (b) the magnetic head installed above the drum; (c) the control and display unit in the operator's cabin (circled).

Figure 3 shows a typical installation on a drilling rig. The most important feature of the automated system is that instead of a handheld data logger, a large control and display unit (CDU) is installed in the operator's console (Figure 3c). The CDU collects data, decodes it, filters it from noise, and then counts the number of anomalies over a given length (6D or 30D). The system will then reference the processed data with the discard criteria for that particular rope. Input of the discard criteria will be done once, during the system's commissioning, as will the two threshold values: critical and precritical. The operator will see these inputs via corresponding yellow and red signals that will inform of the rope's condition, along with a green signal if neither threshold is exceeded. Should an expert opinion be necessary, the system allows data traces to be downloaded to a PC for more detailed analysis, in the same fashion as a normal rope inspection, and formatted into a report. This can be performed remotely, as there is a provision for either a LAN or GPRS connection to the CDU.

Experience and Applications

The use of the automated condition monitoring system is documented in previous research (Slesarev et al. 2008, 2014; Anisimov et al. 2018; Mironenko and Shpakov 2016). Overall, it can be said that the challenges described in the previous section of this paper have been addressed. The result is a convenient and a reliable system, simple in use for unqualified personnel, with minimal interruption to the production cycle and fully independent of the human factor.

It would be fair to expect such a package to be more expensive than a regular magnetic rope flaw detector installation, given that every application will normally require some tailoring of the design and some additional costs for commissioning and installation. For example, the cost of the hardware for an automated condition monitoring system is 15% to 30% more than the cost of a regular magnetic rope testing instrument for the same rope diameter. The installation costs can be considerable, especially if the system is located on a complex machine or on a site with limited access. Nevertheless, these costs are within a reasonable margin and will be eclipsed by the savings they bring. Most of all, the rope will likely remain in operation for its full service life, which will ultimately pay for the investments into the system.

Certain applications, for example mine hoists, may require the monitoring of two or more ropes simultaneously. This requires the installation of several magnetic heads. For example, eight flaw detectors were required for the rope monitoring station at the Moab Khotsong mine in South Africa (Marias and

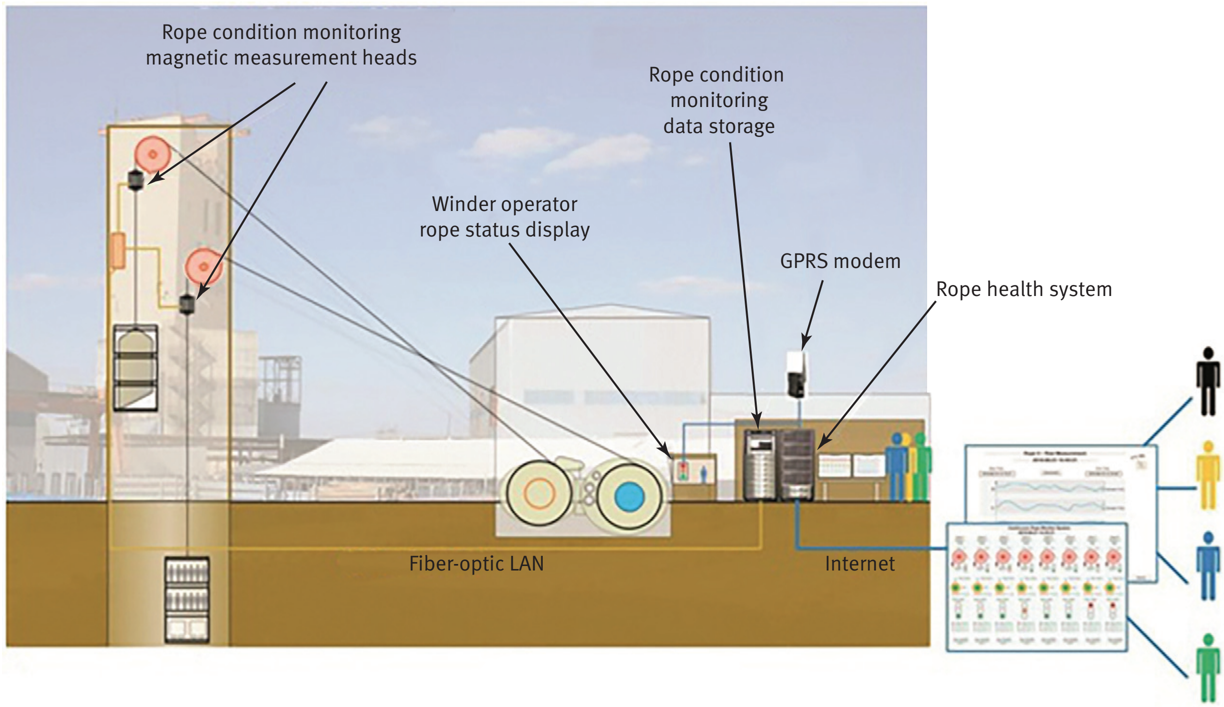


Figure 4. The rope monitoring station is located in the mine control room, where information on the ropes' conditions is streamed continuously.

Bester 2011), as there are two four-rope mine hoists. Figure 4 shows the diagram of the station's setup, which is sophisticated and expensive but reasonable for this extra-deep mine (more than 4000 m deep).

One other application that has been successfully implemented is the installation of a continuous monitoring system for crane ropes at metallurgical plants. In this environment, the ropes are subjected to high temperatures (up to 800 °C), leading to irreversible changes in the crystal lattice of the steel in the wires, which drastically reduces the wires' load-bearing capacity. As of March 2021, six systems are currently operating at the Severstal mill in Cherepovets, Russia, on a section under the pulley of the main hoist trolley, to monitor the most loaded and exposed segment of the rope (Sukhorukov 2007). The magnetic head installation is shown in Figure 2b.

Whereas the absence of a rope testing program has compelled companies to prematurely replace rope, the presence of a condition monitoring system has allowed them to push the envelope in the opposite direction. The aforementioned Severstal mill had a discard LMA criterion of 6%. Through experimentation, it was determined that this margin could be safely increased to 7%. Tracking this deterioration is only possible by continuously monitoring the rope's condition. This margin allowed for up to a 20% increase in the lifetime of the rope (from 1200 to 1500 pouring cycles) (Vorontsov et al. 2013).

Challenges and Limitations

As with any new technology, there are difficulties that accompany the introduction of an automated condition monitoring system. The biggest challenge is that many industries have little experience with regular MFL rope testing, such as onshore drilling and exploration. This lack of experience is often accompanied by the conservative mindset of key managers and operational personnel. Equally important is the necessity to adapt the system, namely the magnetic head, to the specific parameters of the machinery and the surrounding environment. The installation and commissioning of the system can be a tedious process requiring the participation of manufacturer specialists.

Not all types of wire rope are suitable for an automated monitoring system. This primarily concerns nontraveling ropes, such as bridge stay cables, guy wires of flare stacks and masts, conductor and ground wires of power lines, tracking ropes on ropeways, and so forth. The biggest challenge here will be developing a system to periodically articulate the magnetic head via self-moving robots or a set of winches and cables.

From Monitoring to Forecasting

Magnetic rope testing does not fully replace visual inspection, and for a full objective report on rope condition, the found anomalies must be verified. Likewise, MFL data is just one source of data for condition monitoring systems. Generally, steel wire ropes are not repairable, and thus must be discarded if their strength or safety factor decreases below a minimum level. The allowed safety factor is specified in relevant industrial standards that account for hazard class, operating conditions, and degree of risk.

Past theoretical investigations of the load-bearing capacity of steel wire rope did not account for the effect of rope defects (especially internal ones, which are invisible without magnetic rope testing) on its breaking force (Costello 1997; Feyrer 2007; Glushko 2016), where an arbitrary "factor of ignorance" is present in the calculations. Currently a method exists that calculates the residual safety factor taking into account the rope's structure, metallic cross-sectional area, tension value, the breaking strengths of individual component wires, the LMA and LF values (for both external and internal), and their location obtained from magnetic rope testing (Sukhorukov et al. 2014).

Thus, it is only natural to expand this technique into the automated condition monitoring system. The technical requirements lie in the addition of an odometer and tension meter, both which are directly connected to the CDU, enabling the computer to not only record the rope's actual operating time measured in tonne-kilometres (tkm) but also automatically

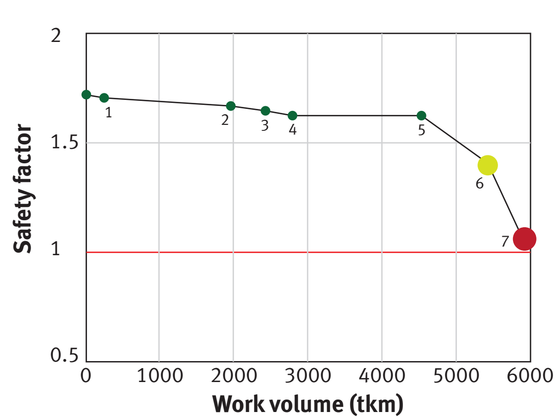


Figure 5. The safety factor as a function of the work volume.

calculate the rope's load-bearing capacity and safety factor.

The system can compute three safety factors: for ropes with no defects and for those with LMA and LF values. In each case, the deformations and stresses caused by tension, torsion, and bending in wires are assessed (Malinovsky 2002). Then, using a suitable criterion (the maximum equivalent stresses, max σ_{eqv}, in the most stressed wires), the safety factor is given as:

$$(1) \qquad n = \frac{\sigma_B}{\max \sigma_{eqv}}$$

where

σ_B is the breaking strength of the wire's material.

The relative strength safety factor reductions of the rope (ropes weakened by loss of metallic area ΔF, and by number of wire brakes *A*) are given by parameters $\chi_{\Delta F}$ and χ_A such that:

$$(2) \qquad \chi_{\Delta F} = 1 - \frac{n_{\Delta F}}{n_0}$$

$$(3) \qquad \chi_A = 1 - \frac{n_A}{n_0}$$

where

$n_{\Delta F}$ and n_A are the respective safety factors of the ropes with defects, and

n_0 is the safety factor of a rope with no defects (in other words, a new rope).

The resulting load-bearing loss is the superposition of the losses due to LMA and LF:

$$(4) \qquad \chi = \chi_{\Delta F} + \chi_A$$

Thus, the overall safety factor of a worn rope with defects is:

$$(5) \qquad \tilde{n} = n_0(1 - \chi)$$

Figure 5 illustrates how the safety factor $\tilde{n}$ decreases with the work volume *N*. Green circles correspond to the operable condition of the rope (inspections 1 through 5). Inspection 6 induces a yellow light, warning the operator that the rope is worn and its condition is approaching discard value. Inspection 7 results in a red light. This means the load-bearing capacity of the rope is fully exhausted and the safety factor is close to the minimum permissible value of 1 (red line).

This data was collected from discrete MFL rope testing data of a drilling rig in West Siberia over a six-week period. The rope was then respooled on the drum up to 270 m to remove the worn-out rope section from the load-bearing length (Slesarev et al. 2008).

Thus, condition monitoring of rope incorporating automated NDT and tension measurements allows the operator to predict the moment of rope failure. This is the final piece that negates the human factor issue, effectively telling the operator how many cycles remain and when to plan respooling or replacement maintenance.

If there is doubt that the system's output is correct, the operator can always double check with a competent expert, by uplinking the CDU to a control center in the manner mentioned previously.

Conclusions

In the past, the quest for new materials and production output came with a safety risk. Current technology mitigates this risk by making safety not only an affordable choice, but an investment.

The described evolution of a versatile flaw detector morphed into an automated condition monitoring system that in turn serves as a service life forecaster is a testament to this simple truth. The growing commercial interest in this new technology further merits that its introduction is timely, both for increasing safety and sustainability in the operation of hazardous machinery.

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