Signal Acquisition and Processing in the Magnetic Defectoscopy of Steel Wire Ropes

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***Abstract* — The system that resolves the problem of wire rope defects using a magnetic method of inspection is presented in this paper. Implementation of the system should provide for full monitoring of wire rope condition, according to the prescribed international standards. The purpose of this system, in addition to identifying defects in the rope, is to determine to what extent damage has been done. The measurement procedure provides for a better understanding of the defects that occur, as well as the rejection criteria of used ropes, that way increasing their security. Hardware and software design of appliance for recording defects and test results are presented in this paper.**

***Key words* — magnetic defectoscopy, magnetic sensor, steel wire ropes.**

I. Introduction

METHOD for analysis of steel wire ropes by means of magnetic defectoscopy was originally patented in Great Britain in the 1960s. The reliable and safe use of steel wire ropes is crucial with mining, oil industry, cranes, ski lifts and elevators, thus there is a constant concern among users and competent institutions about current rope state. Over the years, two different and distinct electromagnetic (EM) methods for detection and measurements of steel wire rope defects have been developed. The first one is Loss of Metal Cross Section Area Inspection (LMA) [5], which quantitatively measures the loss of metal cross section area caused by external or internal corrosion (due to environmental conditions or poor lubrication) and wear (due to rubbing along floors, nicking, high pressures, and/or poor lubrication). The second EM method is Localized Flaw (LF) Inspection, which qualitatively detects a wide variety of external and internal discontinuities such as broken wires and corrosion pitting. Broken wires are usually caused by fatigue, interstrand nicking and martensitic embrittlement. For all the instrumentation used nowadays, no matter which method is used, it is common that strong permanent magnets induce a magnetic flux at the saturation level in the rope in the axial (longitudinal) direction. There are various types of sensors that provide for measurements of the magnetic flux, such as coils, Hall sensors or fluxgate sensors. 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. Aside from the detection of defect, with this system it is possible to determine the level of damage to the rope. The system itself must be agile and convenient to operate in the field, what is hard to accomplish in many cases.

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II. Description of the System

The principal scheme of the system is shown in Fig. 1. The principal elements of the system are a magnetic sensor which encircles the rope under test, a device for data acquisition and primary processing of sensor signals, and a computer that performs secondary processing, display and storage of results.

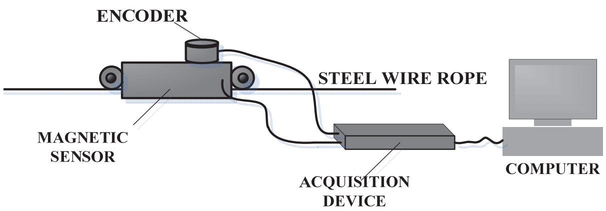


Figure 1. Principal scheme of the system.

A magnetic sensor located on a wire rope generates a voltage signal proportional to the change of the flux through the main cross section area of the rope. A rotary encoder, whose function is to measure the positions of sensors relative to the rope, is in the same mechanical enclosure with the sensor. Signals from the magnetic sensor and encoder are passed to the device for data acquisition and sensor signal processing via separated conductors, protected with metal sheaths. In the device for the signal acquisition, operations of analog processing of voltage signals from sensors and their digitization and formatting in order to be transferred to the computer are performed in the signal acquisition device. PC connection is of USB type. Computer performs display and secondary data processing within the specialized software developed for this application.

III. Theoretical Foundation of the Method

The Main Flux Method uses an annular coil that encircles the rope, together with an electronic circuit that performs data processing, to provide information about existence, type and level of defect. When a rope is magnetically saturated, the axial magnetic flux in the rope is proportional to its cross sectional area [3-6]. Therefore, any LMA can be determined by measuring this magnetic flux. The Main Flux Method determines local magnetic flux inside the rope. Since coils must encircle the magnetic flux to be measured, they can directly measure the magnetic flux inside the rope. Since it measures the magnetic flux inside the rope locally, the annular coil approach offers uncommon resolving power, signal fidelity and, therefore, inspection accuracy [5]. Fig.2. shows a wire rope within a magnetic sensor, the magnetic field lines are also indicated.

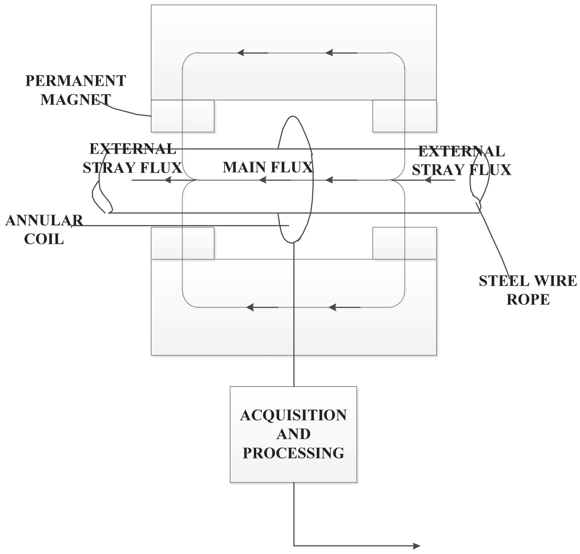


Figure 2. Internal structure of a magnetic sensor.

Wire rope is saturated under the influence of strong permanent magnets, and the induced magnetic flux is shown in Fig. 2. Since this system uses the LMA method [3], the selected coils need to be wrapped around the wire rope. This method uses the main flux, while the external stray flux is used to obtain additional information that are not part of this method [1-2]. The main flux in the segment of the rope under test is given in equation (1).

$$\Phi = B \times S \,. \tag{1}$$

Magnetic induction B is approximately constant since the magnetic rope is in magnetic saturation. Electromotive force E induced on the basis of a change of the flux in time during movement of the rope through the sensor module with N coils is given by equations (2) and (3).

$$\varepsilon = N \times \frac{\partial \Phi}{\partial t} = N \times \left(\frac{\partial B}{\partial t} \times S + \frac{\partial S}{\partial t} \times B \right). \tag{2}$$

$$\varepsilon \cong N \times B \times \frac{\partial S}{\partial t}. \tag{3}$$

For the moving rope, metal cross section is a function of the length what is the goal of this type of non-destructive testing. Therefore equation (3) can be reduced to the following form.

$$\varepsilon = N \times B \times \frac{\partial S}{\partial l} \times \frac{\partial l}{\partial t} = N \times B \times v \times \frac{\partial S}{\partial l}. \tag{4}$$

Effective metal cross section of the main flux at some point along the rope l is given in equation (5), where l represents the longitudinal coordinate of the rope, d is median length of magnetic flux in the ropes, and x current coordinate of magnetized rope. The expected minimum signal level, the electromotive force in V is given by expression (6).

$$S(l) = \frac{1}{d} \int_{l}^{l+d} S(x)\,dx. \tag{5}$$

$$\varepsilon = 2 \times 10^{-4} \times N. \tag{6}$$

It is important to note that the rope speed value in the expression (4) is 1 m/s what is the usual standard speed of the rope in non-destructive testing, rope saturation induction is about 2T, and change of the metal cross section is 0.10 mm2/mm. Detection of impairment loss of metal on a rope is achieved with an integrated main flux signal, while for other defects such as corrosion the original and differentiated signal from the sensor (coil) are of great importance.

IV. Hardware and Software of the Acquisition Device

The acquisition and primary signal processing in the system is accomplished by the device consisting of circuits for processing of analog and digital signals. The block representation of the device is given in Fig 3.

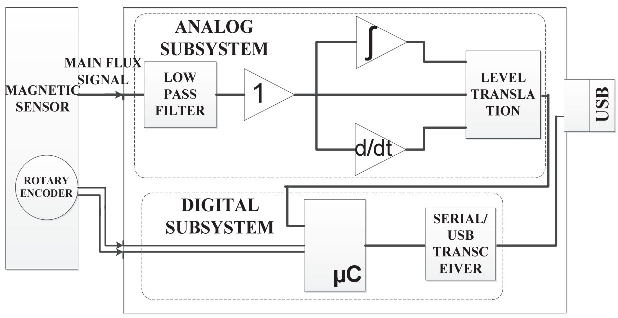


Figure 3. Block representation of the acquisition device.

The main flux signal is fed into the analog subsystem where it is processed. In order to fulfill the requirements for sampling freqency and avoid overlapping in the spectrum of digitized signal, the signal is passed through a low pass filter first. It is a resistor-capacitor filter with cut-off freqency of 1000 Hz. The output of the low pass filter feeds a unity gain amplifier. The purpose of the amplifier is to isolate input and output stages and provide for high impedance input for the sensor signal which is intrinsically of low amplitude and low power. Then, the signal is routed to the inputs of integrator and differentiator and by the level translation block to the digital subsystem of the analyzer. Since the analog processing of low power, sensitive-to-noise signals is done in the device, special attention was paid to use of components, primarily operational amplifiers, with high surpression of CMRR (PSRR), which are not themselves sources of noise. Besides, the analog subsystem of the device is supplied from its own battery power supply, in order to minimize the influence and the crosstalk from digital subsystem and/or the enviroment.

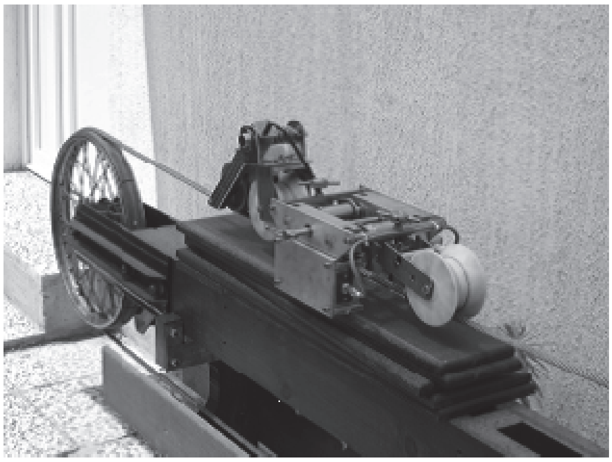
Digital part of the device consists of the microcontroller ATMega16, whose input pins are connected to the signals from the analog subsystem and the rotational encoder. The signals processed in the analog subystem are digitalized by means of 10-bit SAR AD converter integrated within the microcontroller. The acquisition freqency is determined by a timer clocked by a precise crystal oscillator. The microcontroller features 1k RAM memory [7], enough to implement three low pass FIR filters for three signals from the analog subsystem. The filtered signals' values are, together with the position obtained by reading of incremental rotational encoder, packed in messages serially transferred to a PC. USB connection is implemented by means of external integrated circuit FT232RL featuring a bridge between the microcontroller's UART and the PC's USB interface. When designing a custom software application it is not required to perform extensive signal processing in microcontroller. However, there are existing software solutions on the market nowadays, so it is necessary that complete signal processing is carried out. Sampling is performed with a higher frequency than expected bandwidth and afterwards digital filtering is done locally to reduce the data flow through USB connection to the computer.

The microcotroller software is divided into a main programme and interrupt routines. The incremental encoder is read by means of two external interrupts sensitive to level change. This way, the maximum (x4) encoder resolution is easily obtained. Scaling of the position is done in the interupt routine, on the basis of a constant written in the microcontroller's EEPROM during the process of calibration. The AD converter is clocked by a timer set to start conversion in accordance with the desired acquisition freqency. The functions implementing FIR filtering are also called from within the interrupt routine. Due to the microcontroller's speed, the mathematical operations are done in a Q15 fixed-point format. The serial communication is realized in master-slave form, where the PC is the master and the acquisition device is the slave. The PC starts and stops data transmission by sending command messages, but the timing is determined by the device. In the main programme, initialization of the microcontroller's perpheries and the implementation of a simple state machine synchronizing the other software elements is performed.

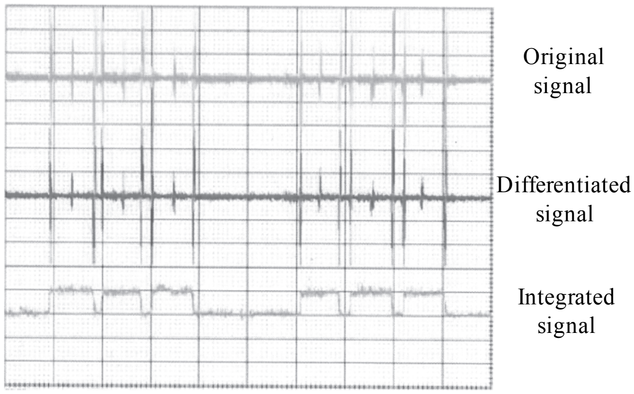
The computer executes a program written in LabWindowsCVI application which performs reception, presentation and storage of data in the form of ASCII csv (*coma separated values*) file suitable for reading in a variety of software packages such as MATLAB.

V. Prototype of the System

A Prototype of the system is designed using commercial off-the-shelf components. The Innovation Centre of the School of Electrical Engineering in Belgrade carried out a series of measurements with the described system on the lift model designed specifically for the test (Fig. 4a). A variable rotation speed electric motor drives an experimental model of the lift, while the magnetic sensor and the rest of the system are static. The signals obtained in one round of testing are shown in Fig. 4 b).



a)



b)

Figure 4. a) Experimental system set up for testing in laboratory conditions and b) display signals during testing.

The peaks on the original signal provide information on discontinuity and loss of metal in a steel wire, while the length of defect is noticed in an integrated signal. The differentiated signal is used as needed to shape the signal for further comparison with the charactristic signals obtained from the typical defects.

VI. Results and Regulations

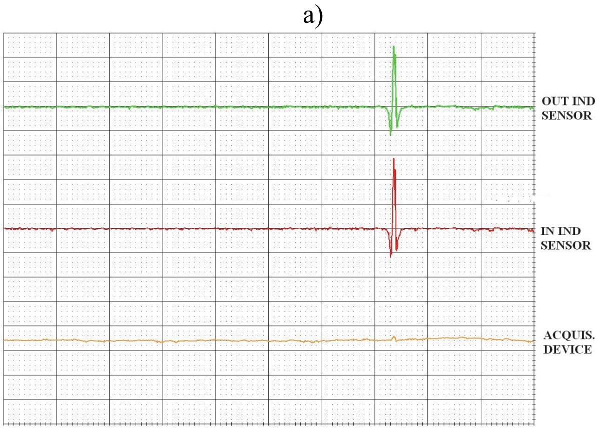
The results presented below have been obtained during field testings combining different types of sensors and monitoring various defects of steel wire ropes. The main purpose of the method is to examine the steel wire rope in conditions where it is installed, without the disruption of the work process or installation. The testing should be done in a short time and should provide for records that could be subsequently analyzed.

Nowadays, magnetic defectoscopy is a very useful method for testing condition of steel wire ropes worldwide. European Standard EN12927, American Standard ASTM E 1571, as well as numerous professional organizations and associations have included this method as a valid standard. In Serbia, this method has been used for more than 20 years, what caused that the magnetic defectoscopy is included in the technical regulations as a permissible method for testing of steel wire ropes [8].

NDT method that provides assessment of the steel wire rope condition using magnetic defectoscopy is based on accepted norms that regulate this matter. Magnetic defectoscopy provides highly reliable data about rope condition, therefore the segments where defects were identified can easily be localized. By combining signals from multiple sensors it is possible to describe the observed changes in the geometry of steel rope both qualitatively and quantitatively. In this way, it can be determined whether the observed changes in the steel rope are in the range of standard limits, near the limit values or even exceed those values. Assessment of condition of steel ropes, based on the results of NDT magnetic defectoscopy, is conducted in accordance with applicable regulations and standards.

Before testing, simulations of known defects are performed in order to calibrate each sensor. Fig. 5a) shows the damage to the steel wire rope created by mechanical shock on the rope. A typical display of the results that show this defect as a function of its position is given in Fig. 5 b).

a)



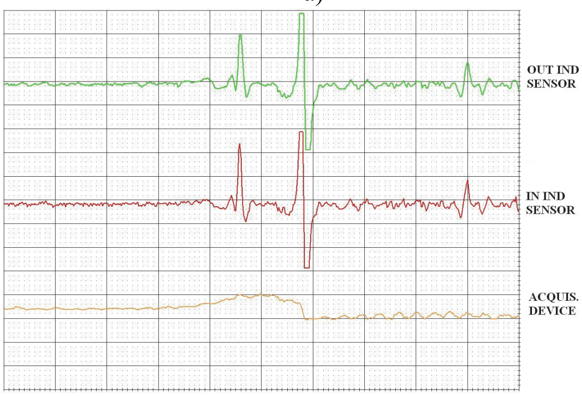
b)

Figure 5. a) Mechanical shock on steel wire rope b) display signals during testing of this defect.

Top signal with 25mV/div resolution is obtained from the outer inductive sensor, while signal in the middle is from the internal inductive sensor (resolution 10mV/div) where the defect is clearly visible. The bottom signal (resolution 100mV/div) is an integrated signal from acquisition devices. Two top signals show that defect is present and the defect's position.

Integrated signal in the place of defect shows detected irregularity and its intensity is proportional to the loss of metal in cross section which is very low in this example. Another type of defect that is common is broken wires in the steel wire rope (Fig. 6 a).

a)



b)

Figure 6. a) Broken wire defect in steel wire rope b) display signals during testing of steel wire rope with this defect

The system of sensors detects damage and displays it as shown in Fig. 6 b). Thanks to a system of various types of sensors it is possible to clearly detect start of the defect, type of defect and its position thanks to a signal from the rotary encoder. The number of broken wires inside the rope is possible to determine from the amplitude of the bottom signal. The loss of metal in cross-section due to broken wires should be calculated by taking into account its number and cross section at the reference length.

Due to the complex wire rope defects, damage to a greater number of wires that steel rope is made of, each interrupt or interfere individually can be noticed. One such example is given in Fig. 7.

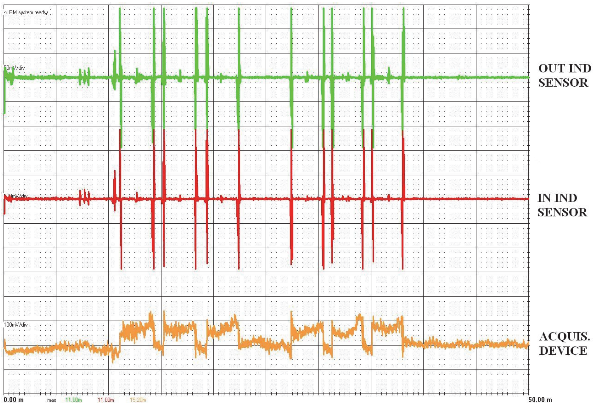


Figure 7. Display of complex defect signals on steel wire rope, a few consecutive defects together

The results arising from the application of these methods are highly important and relate to the following: eliminate the human factor as less reliable in the process of regular monitoring of steel ropes; Increased safety of staff and equipment in the work process; Provide identification of hidden defects and damage; Provide a record of steel rope condition taken after NDT; Better assessment of steel rope condition taken in the process of making a decision about further use, the possibility to extend the use of the steel wire rope in accordance with the results of NDT.

In addition to NDT magnetic defectoscopy and its analysis of record, overall assessment of the steel wire rope condition depends on conditions of operation, quality and scope of maintenance, compliance with regulations governing the required type of installation and the quality management system applied by the user.

VII. Conclusion

The presented system provides an effective inspection of wire ropes and determination of the current condition of ropes. Measurement procedure is used to identify damage to ropes and provides for information on the type and extent of defects, while complying with the technical regulations and standards governing the non-destructive testing of steel wire ropes. Testing has shown that the system is reliable, compact, easy to use and suitable for field work in difficult conditions, what is often the case in practice.

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