Quantitative Inspection of Broken Wire in Wire Ropes: Method and Apparatus

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This article introduces a complete system for automatic inspection of broken wire in wire ropes. The development of this technique is reviewed. It is followed by a description of the hardware and software of the apparatus. The hardware uses magnetic concentrators and Hall-effect sensors. Signal analysis is based on wavelet processing. Quantitative identification of broken wire in wire ropes is based on a pattern recognition approach of the neural network.

1. INTRODUCTION

Wire ropes are widely used in many industrial fields. Without exception, failure of wire rope causes expensive damage to equipment or even loss of human life. In order to prevent this kind of failure, it is very important to determine reliably and accurately the condition of the running rope.

Ropes are primarily checked for two types of deterioration. One is broken wire; the other is a change of rope diameter. It is more difficult to check broken wire than a change of rope diameter. The most obvious and the simplest method of detecting rope flaws is by means of visual inspection (Weischedel, 1981), but the reliability of this method depends on the experience and attention span of the inspector. Another method of avoiding danger is to replace ropes at regular intervals without prior testing, which is neither reliable nor economical (Jentgen, Rice, & Anderson, 1984).

The art of wire rope inspection has progressed rapidly over the recent years. Electromagnetic instruments that can reliably test wire ropes in service are now available (Weischedelet & Ramsey, 1989), but many of them cannot detect wire flaws quantitatively.

Quantitative determination of test signals is difficult, because the structure of wire rope is complex and the inspection environment is adverse. The researchers of Huazhong University of Science and Technology have been working on this since 1988, and a series of results (Li, Yang, Lu, & Wang, 1990; Wang, Shi, & Yang, 1988) have been achieved. This article describes new approaches and apparatus for carrying out real-time automatic quantitative inspection of broken wire in wire ropes.

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2. INSPECTION INSTRUMENT

In order to test wire rope in service, compact light-weight equipment has been developed. It can be used under all required operation conditions, it can reliably detect a wide variety of rope flaws, and it can be operated conveniently by moderately skilled operators. This instrument and its main technical specifications are shown in Figure 1 and Table 1. It is composed of an electromagnetic flaw detector, a sampling controller, an analog signal preprocessor, an Analog/Digital (A/D) converter, and a microcomputer analysis system.

3. DETECTOR

The principle of the detector is based on magnetic leakage testing (Kalwa & Piekarski, 1987a), which is currently the most reliable nondestructive testing method for the inspection of wire ropes in service. During the period of testing, a rope is magnetically saturated by permanents and run through a magnetic field. Any inhomogeneity, such as a broken wire, causes a change of the flux pattern, which is detected by searching elements.

The magnetic detector is comprised of two essential components. One of them is the magnetizing assembly to magnetize the rope in the longitudinal direction of the rope. It determines the main size and weight of the detector. In order to make the detector small and light, an optimal method has been developed to design the structure of the magnetizing assembly. The magnetic sensors that are used to inspect the leakage magnetic flux are the other component.

<table>
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<tr>
<th>TABLE 1. Main Technical Specifications</th>
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<tr>
<td>diameters of ropes</td>
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<td>testing speed</td>
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<td>quantitative ratio</td>
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<tr>
<td>longitudinal distinguishing ability</td>
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<td>detector weight</td>
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Because of their sensitivity to magnetics, integrated Hall-effect plates have been adopted in the detector (Kalwa & Piekarski, 1987b). Since, in general, a Hall-effect plate is too small to sense all leakage magnetic flux distribution around an inspected rope, the magnetic concentration technique to solve this problem has been developed (see Figure 2).

The magnetic concentrator concentrates the magnetic leakage flux around the surface of the core rope and inducts the flux into a Hall-effect plate, which is put in the middle of the concentrators. The array of the magnetic sensors is put along the circumference of the wire rope and carries out the nonmissing test. It can also improve the tested strength of magnetic leakage flux and the signal-to-noise ratio of testing signals.

4. SAMPLING CONTROLLER AND PREPROCESSING OF ANALOG SIGNALS

The magnetic leakage flux distribution of a rope is a space variant rather than a time variant. If the sampling for a sampled signal is in the time domain, it is strongly affected by rope inspecting velocity. The sampling interval in the space coordinate axis will extend or shorten when the inspecting speed is faster or slower. That is why it is difficult to use this range data to provide useful information.

The sampling controller's rubber wheel—pushed to the inspected rope by a torsional spring—rotates along the rope during inspection. It turns a concentric rotary grating, which controls the microcomputer operating the sampling of the A/D converter on the same space interval. The space interval between two adjacent impulses is of equal length \( D_s \) in the space domain; here \( D_s = 2 \text{ mm} \). The space domain sampling array is \( X_s(i \cdot D_s) \), its equivalent time domain array is \( X_t(i \cdot D_t) \), \( i = 1, 2, 3, 4, \ldots \). The time interval \( D_t \) will be of equal length if the rope inspecting speed remains constant. Because \( X_s(i \cdot D_s) = X_t(i \cdot D_t) \), \( i = 1, 2, 3, 4, \ldots \) \( D_s = V_{\text{max}} \cdot D_{\text{tmin}} \), here \( D_{\text{tmin}} = D_s/V_{\text{max}} = 2 \text{ mm}/(2 \text{ m/s}) = 0.001 \text{ s}, f_{\text{max}} = 1/D_{\text{tmin}} = 1000 \text{ Hz} \).

The preprocessing of analog signals that are outputs of Hall-effect plates includes two steps. First, the analog signals are amplified. Second, the amplified analog signals are filtered by a low-pass filter to remove some high-frequency interference. The cut-off frequency is higher than \( 1.5 f_{\text{max}} = 1500 \text{ Hz} \). The filtered analog signals are then converted to digital signals by the A/D converter at the controlling of the sampling controller.

5. DIGITAL SIGNAL PROCESSING

The broken wire signals are distorted by two kinds of frequency composition. One is the low-frequency interference caused by strand signal, rope speed fluctuation, the sliding of the
rubber wheel of the sampling controller, and the magnetic concentrator. The other is high-frequency random signals, caused by the shaking of the tested rope, random electric interference, and impulsion caused by broken wire ends, while the ends pass the sampling controller and enter the detector, and so forth.

A digital signal processing method must remove the interference of different frequency bands as much as possible, so it must have the ability of frequency processing. In order to identify the location of broken wire on an inspected rope, the digital signals after digital processing must retain the space domain distinguishing ability, too. Therefore, the digital processing method should have the ability to simultaneously process digital signals in the frequency domain and in the space domain. That is, in fact, the advantage of wavelet (Daubechies, 1988; Mallet & Hwang, 1991).

The digital signals are decomposed into five $2^j$ scales ($j = 1, 2, 3, 4, 5$) by the dyadic discrete wavelet (here, from $j = 1$ to $j = 5$); the frequency band of a scale is twice as high as the next scale; the $2^1$ scale corresponds to the sampling frequency band. The decomposed signals in each scale have two parts. One is the low-frequency part of $s_{2j}$, which contains the signal composition of lower scale, the other is the high-frequency part of $w_{2j}$, which is the signal composition of this scale.

The $w_{24}$ corresponding to the high-frequency interference and the $w_{24}$, $w_{25}$ corresponding to the low-frequency interference of the magnetic concentrator and strand are removed during reconstruction. The digital signals are modified by means of removing the different frequency interference. The reconstructed signals still retain the space domain distinguishing ability. Figure 3 illustrates the tested digital signal of $\phi$ 18 ($6 \times 19$) running rope and its wavelet processing.

The two-order B-spline symmetry filter is used here. It has two main advantages. One is that the sudden change of the original signal corresponds to $w_{2j}$ peaks on all scales in the same

![Figure 3. Original signal and reconstructed signal.](image-url)
place (see Figure 3), so this filter is suitable for peak testing. The other is that the filter length is short, so there is relatively little computing.

The testing length of a rope is usually hundreds of meters, so the amount of testing data is bulky. However, the wavelet can only process a certain amount of data. It is also unnecessary to restore all sampling data. The difference threshold method (Wang, Shi, & Yang, 1988) is used to abstract abnormal signals, which include signals of broken wire and their location during sampling. Only signals of a limited length, symmetrically located at two sides of an abnormal signal, such as 32 points, are restored. The wavelet analysis is then carried out after sampling.

6. RECOGNITION OF THE NUMBER OF BROKEN WIRES

Because the amplitude and space distribution of broken wire are synthetically affected by the numbers of broken wire and the distance between broken ends, it is difficult to create a direct function between the broken wire and tested signals. Therefore, the pattern recognition method based on supervised learning is adopted in quantitative inspection of broken wire. The three-layer back-propagation (BP) neural network (Lippman, 1987; Widrow, Winter, & Baxter, 1988) is used in this apparatus.

Ropes that belong to the inspecting range of the apparatus are divided into different kinds according to their construction, diameter, material, and running condition. Choosing a rope of each kind, typical combination types of different numbers of broken wires with different distances between broken wire ends are artificially modeled on the rope in the laboratory. After the rope is inspected by the apparatus, the patterns of these typical combination types are received. Figure 4 demonstrates a wavelet-processed signal of man-made broken wire in a rope, the same kind of rope as in Figure 3.

The pattern recognition of the BP neural network includes two steps. The first is teaching the network. Known patterns are used as learning samples during the learning step. The BP neural network adjusts its weights and thresholds through the learning of the learning samples. The second is the working step. The local abnormal signals of an inspected rope are detected and processed by the apparatus to form some patterns of abnormal signals. These patterns of abnormal signals are then sent to the BP neural network to compare with the existing known learning samples, and the quantitative inspection of broken wire is carried out.

7. CONCLUSION

The apparatus described in this article, based on the magnetic concentrator, wavelet decomposing and reconstruction, and the BP neural network pattern recognition technique successfully realizes the quantitative inspection of broken wire in wire ropes. It is a small and light portable instrument. The apparatus operates under a human–computer interaction model. The operator should choose different menus according to the diameter, material, and structure of the inspected rope before inspection.

Figure 4. A learning sample of broken wire.
The accuracy of quantitative inspection depends on the numbers of learning samples. It is influenced by the running state, such as wear and rust, of the rope. It is usually difficult to modify the learning samples according to the running state of a particular inspected rope. This is the main reason why the accuracy of this apparatus can only reach 70%, and it is also the main problem that is being solved.

The apparatus can be used to inspect common ropes of elevators and mine hoists.

REFERENCES


