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Application of signal analysis in magnetic testing of wire ropes

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The paper presents the method that allows to determine the lay length for wire ropes in service from the results of their magnetic examination. The method was designed as a result of local fault sensor signal (LF) analysis, which is a basic method in non-destructive testing of wire ropes. The method employs spectral noise analysis of the LF signal to yield the lay length of ropes and strands, including the lay length of the internal strands of non-rotating ropes. As such the method can be used not only for typical magnetic examinations of wire ropes in service but also for the examination of torque behaviour of non-rotating ropes. Essential points of the method are followed by a case study that demonstrates its applicability.

1. Introduction

Traditionally the magnetic examinations of wire ropes allow the determination of rope Loss of Metallic Area (LMA) [5] and Local Faults (LF) [11]. These are two main and world wide used determinants of rope condition by the way of magnetic non-destructive method and in most circumstances their application and some practical knowledge allows reliable quantification of wear in the examined rope.

In practice the magnitude of those two signals is analysed [1, 9]. However, some ropes may wear differently. Wear of multi layer non-rotating ropes (Fig. 2) in particular cannot be easily determined based on traditional magnetic examinations [3]. Each rope in service is twisted and untwisted many times. Finally, its mechanical endurance becomes reduced. It is common knowledge that this kind of behaviour could be observed by the measuring the changeable lay length (LL) of the rope.

Some of non-rotating ropes fail as a result of excessive torque applied to the internal rope strands that results in their destruction. In 1996 this

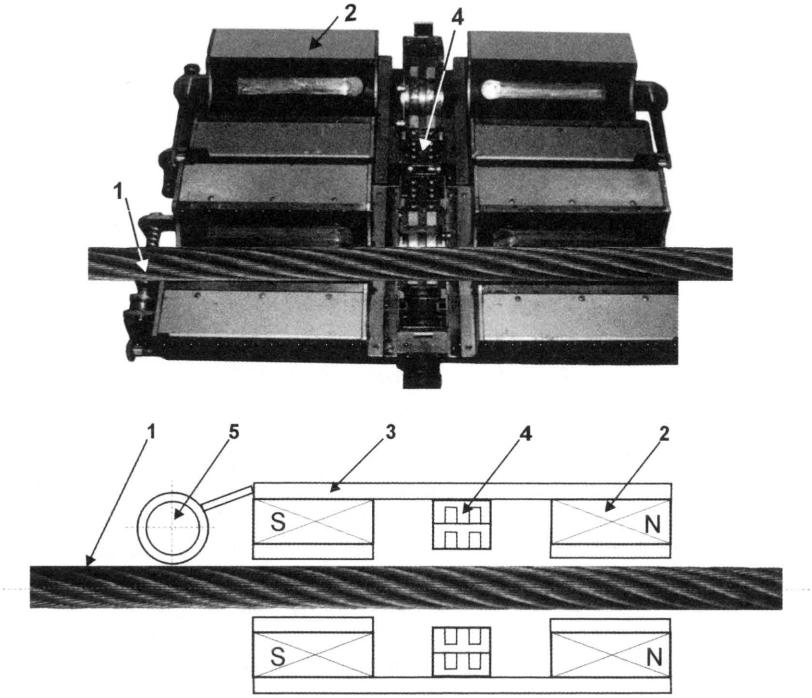

FIGURE 1. Schematic diagram and one of typical NDT head and the arrangement of the sensors for determining position, local faults and loss of metallic area. 1 – Permanent (rare earth) magnets;. 2 – Keeper; 3 – LF and LMA sensors; 4 – Position transducer; 5 – Tested wire rope.

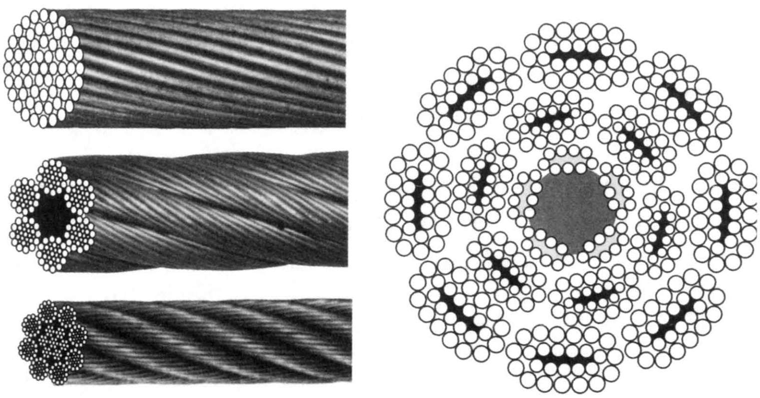

FIGURE 2. Typical spiral and stranded wire rope constructions: spiral, six strand rope with IWRC and FC, multi-strand (nominally torque balanced) rope.

happened at the Bogdanka Mine in Poland where a non-rotating tail rope was destroyed and at Cassidy Shaft (1997) in Western Australia where a multi-strand non-rotating head rope was destroyed [4]. Both ropes were subject to magnetic and visual examinations several weeks before the failure, neither of which had indicated the incoming failure. It shows that classical magnetic method has limitations that should be improved.

This paper presents the method that allows us to detect the imminence of this type of failure by monitoring the length of lay, and its changes, in both external and internal strands of the non-rotating ropes. The monitoring is possible by relating selected characteristics of the LF signal noise to the rope lay length using conventional noise analysis techniques [2, 8].

2. Implementation of digital analysis of the LF signal

The first digital equipment used in the nondestructive testing of wire ropes was the Meraster MD120 data acquisition unit [7]. It is equipped with a SRAM type PCMCIA memory card. The system enables transferring the digital signal from the GP2S test head to a computer where it could be analysed using an appropriate software. Figure 3 is presented the most practical

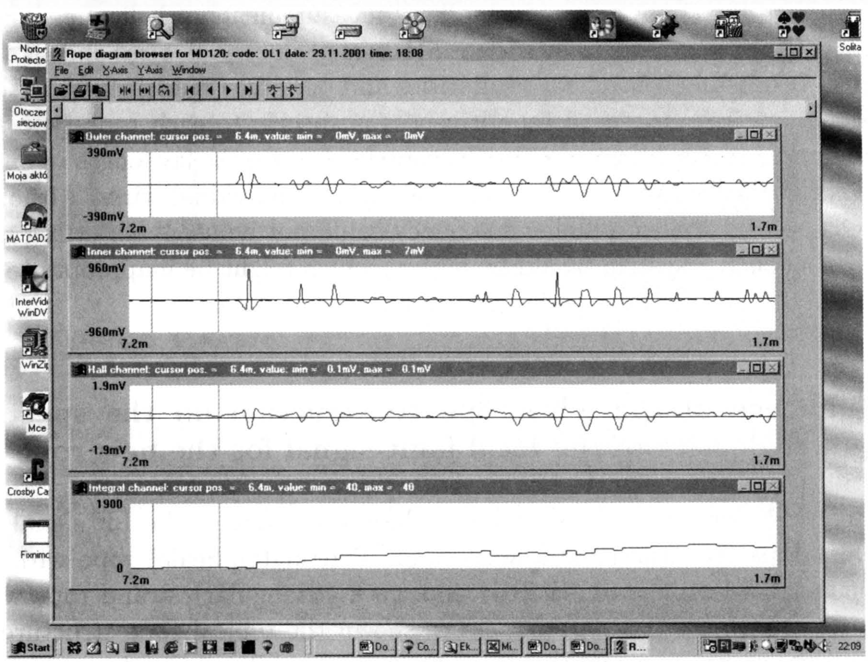

FIGURE 3. Window of the Browser software.

way of analysing the signal from the NDT magnetic tests: visualisation by Browser software [12].

The general arrangement of the GP2S equipment is shown in Fig. 1. In this equipment, the LF signal is produced as a function of the rope position, (rather than time). The rope position is measured by the roller mounted at one end of the test head (Figs. 1-4), and this principle according to one reading is performed every 2.5 mm. As the rope moves in the head of the apparatus during its magnetic examination the relative positions of strands and wires within the head change reflecting the changing rope geometry. This change generates a noise of the LF signal. Repetitive character of changes in rope geometry is reflected in the periodic character of the noise, or of some of its components Thus over a length of 1 m, 400 local fault readings will be taken. Hence, at a rope speed of, for example, 1 m/s, the data acquisition rate will be 400 Hz.

In the book [11] it was shown that such a digital signal may be converted into frequency components using a standard Fast Fourier Transform (FFT) or Discrete Fourier Transform (DFT). The transformation may be used to analyse the "characteristic frequency" component of the LF sensor signal. Given a 400 Hz digital representation of the signal, we can detect frequencies up to 200 Hz, which are created by the regularities in the rope construction, which are greater than 5 mm in length. This data acquisition frequency is high enough for application which allows measurements of helical geometry of wire ropes with different structures. Helical geometry of wires and strands in ropes results in geometrical regularities and periodic repetitiveness of their construction. The degree of repetitiveness is specific to each rope type and construction and is determined by the rope lay length, the lay length of external and internal strands, of the rope core and of individual wires. Although there is no reason why a higher frequency could not be used, admitting that the cost of such a system would be higher, which might be inappropriate for practical use and for storage larger amount of test data.

3. Influence of the wire rope construction on the spectral power density of the local fault signal for the new rope

Figure 4 presents two examples of digital analysis of the LF signal for different rope constructions: a six strand (Warrington-Seale) rope with independent wire rope core (IWRC) and a six (triangular) strand rope with fibre core (FC). At the top of Fig. 4 is shown the typical rope structure of both these six strand rope constructions. In the middle od Fig. 4 is presented the digital LF traces obtained from testing these ropes with magnetic non-

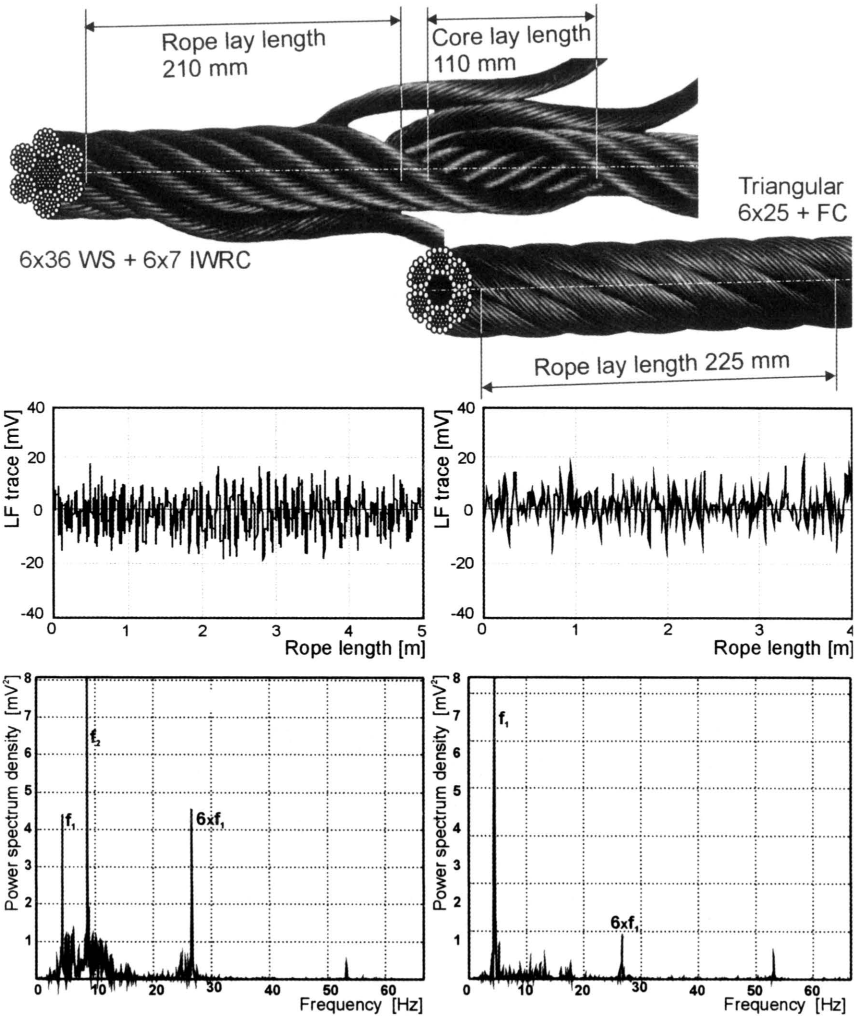

FIGURE 4. Frequency analysis of LF traces for typical six strand ropes.

destructive equipment. At the bottom of Fig. 4 is shown the power density spectrum for each of these LF traces.

At the velocity of 1 m/s the inverse of the frequency given by the power density analysis gives the rope length of interest:

$$L_x\,[\mathrm{mm}] = 1/f_x\,[\mathrm{Hz}], \qquad \text{and}$$

$$f_{\mathrm{rope\,LL}} = \frac{f_{\mathrm{strand}}}{N} \quad \text{(for a } N \text{ stranded rope).}$$

In the case of triangular strand rope with fibre core, the first spike on the chart at 4.4 Hz (f_1) corresponds to the lay length of the rope (Fig. 4 at the bottom, right side). A secondary peak is attained at the frequency of 26.7 Hz ($6 \cdot f_1$), which is the strand length – that is the distance between the two valleys either side of a strand – and is one sixth that of the lay length (in a six strand rope). Turning to the Warrington-Seale rope with IWRC, similar peaks can also be seen on the power density spectrum at 4.5 Hz (f_1) and 26.5 Hz ($6 \times f_1$). In addition to the information on the rope lay length the peak at 8.7 Hz (f_2) corresponds to the lay length of the independent wire rope core.

4. Measurement of variation in strand lay length

In order to assess the feasibility of this method as a practical means of measuring the lay length of a rope in service, a series of tests was conducted on a single length of rope, which was subjected to varying degrees of twist. The equipment used is shown in Fig. 5. A 16 mm diameter 6×19 Seale + FC rope was used in this series of tests for 30 different states of twist, in both the

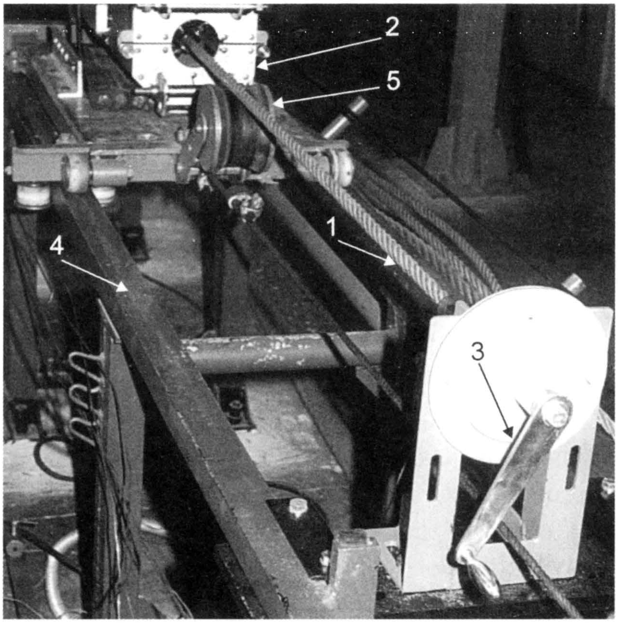

FIGURE 5. Test equipment. 1 – test rope; 2 – NDT testing head equipped with LF sensor; 3 – handle for putting twist into the test rope; 4 – track for the test head carriage (5) to run along the rope.

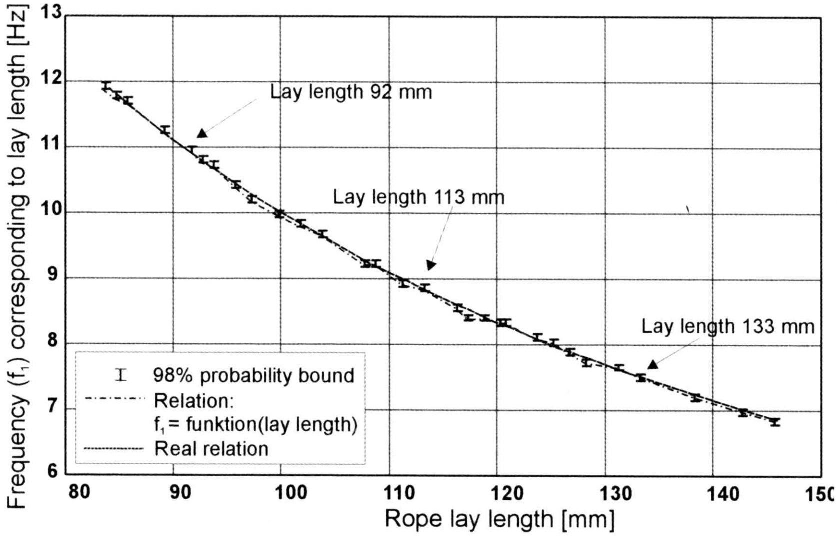

FIGURE 6. Frequency variation as a function of lay-length.

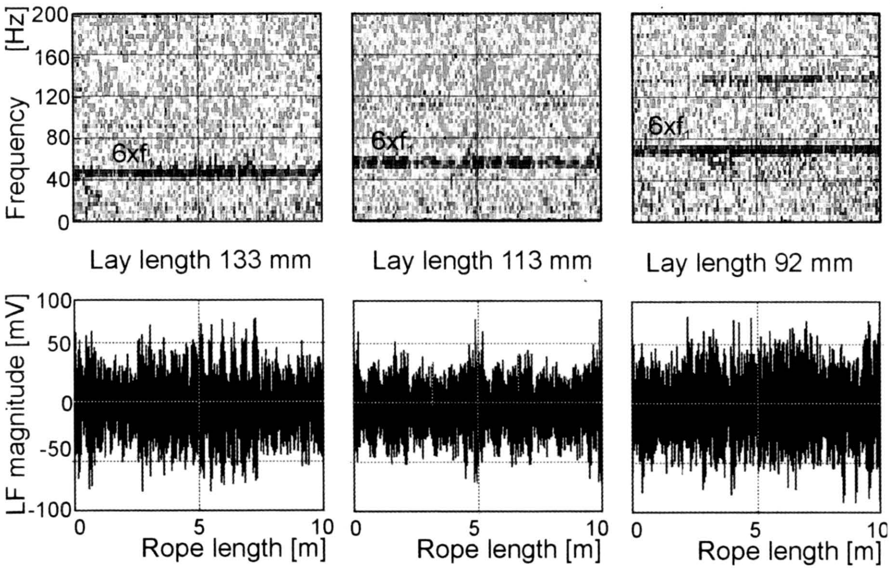

FIGURE 7. Spectrograms of the results of three different tests.

laying-up (shortening) and unlaying (lengthening) directions. One end of the rope was restrained, whilst the other was attached to a rotating device that allowed twist to be put into or taken out of the rope. Each state was measured with forward and back passes of the NDT head 3 times, and an average value of lay length measurement taken, giving 30 sets of measurements at different lay lengths. The rope was held under a nominally constant tension during testing in order to hold it straight so as to allow the NDT head to move. The initial measured lay length was 114.5 mm, and was varied over 73% to 128% of this value. Some of the results of three tests are presented in the form of spectrograms (STFT) of noisy LF traces in the Fig. 7.

5. Practical applications of the technique

5.1. The lay length of the rope measurement

The most practical use is expected in very deep mine shafts to check torque of non-rotating wire rope tail and head ropes and in guy ropes. The technology is similar classical magnetic testing – either mount the test head and run the rope through, or move the test head along the static rope. It could be also used in mine hoisting applications for checking the load sharing between hoist ropes in multi-part winding systems; LL should be the same to ensure correct operation through out.

Possibilities with the proposal of the use of variable LL rope to check LL along the length of the suspended rope, rather than at a few limited locations (e.g. at the bank). The measurement of LL would be implemented as an assessment of the condition of the rope. The value of the elongation can be measured and used as sufficient warning of the rope condition.

Measurement of the level of torsion in a rope will be a function of not only the lay length, but also a function of the load. It means that the torsional momentum could be predicted and its changes observed. These observations could be used practically also for mooring ropes working on off shore platforms and installations.

5.2. The inspection of the inner layer of the non-rotating ropes

Let us pass to the study of the failure of non-rotating rope at Cassidy Shaft. Figure 8 presents the first 250 m of records taken during the magnetic examination of this rope performed several weeks before its failure. The total length of the rope was in exceeded 1200 m. Apart from several broken wires, distributed randomly along the length of the rope and several indications of

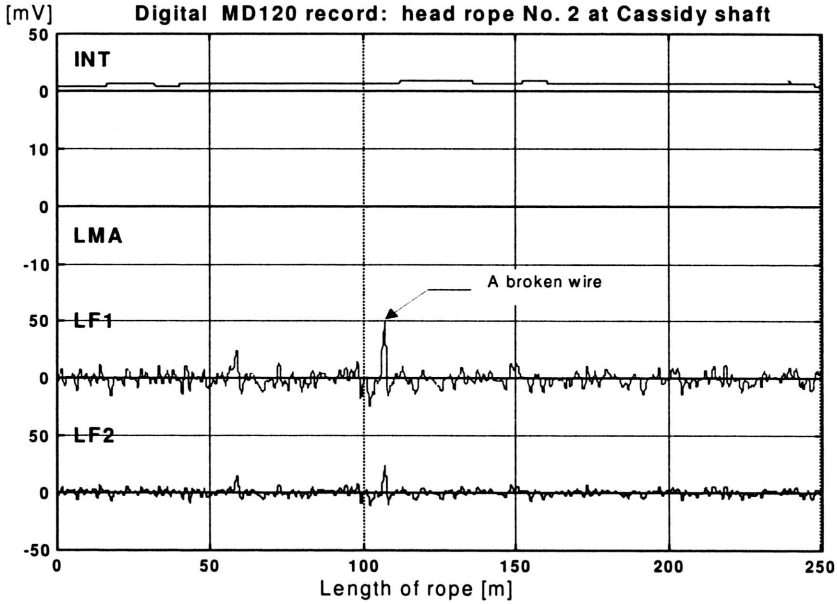

FIGURE 8. Record of magnetic inspection of the non-rotating rope at Cassidy Shaft shortly before rope failure. LF1 and LF2 – record of LF signals (1 – internal coil, 2 – external coil). LMA – record of LMA signal (Hall-effect sensor). INT – record of LF1 integrator.

minor deformations, no other problems were noted nor was the internal or external damage of any form indicated during this examination.

The rope failure occurred roughly at the 200 m from the mark shown in Fig. 8. After the failure another magnetic examination of discarded rope was made. It has indicated the LMA in excess of 100 mm^2 at the point of failure, roughly equivalent to the cross-section of all internal rope strands. The failed part of the rope was cut out, opened up and examined visually. Figure 9 illustrates the type of the encountered damage. In the damaged part of the rope approximately 130 mm of the IWRC was missing altogether. The internal strands immediately adjacent to the IWRC were twisted and plastically deformed (see Fig. 9), with heavy nicking on all undamaged parts of the wires. The measured lay length of internal strands at the point of failure was 75 mm as opposed to 120 mm measured at the distance of 2 m from the damage and 160 m at the intact end of the rope. Only minor damage was observed in the external strands in the form of wire nicking.

It was obvious that the IWRC and internal rope strands have failed as a result of excessive torque forces. In normal conditions the forces involved

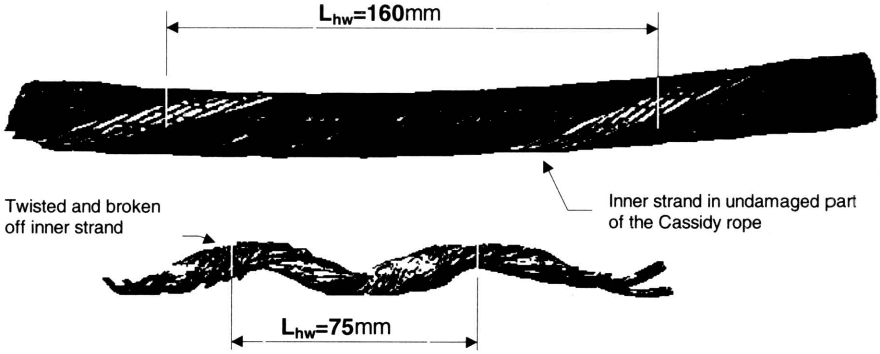

FIGURE 9. Failed part of the Cassidy rope. Intact internal rope strands are shown on the top and one of the damaged strands at the bottom.

would be dissipated as a result of relative movement of strands and wires (moving stress wave) but in this case the relative movement of the internal strands appeared to be arrested. The reason for the latter was believed to be rope internal corrosion, wear, and lack of lubricant resulting in high friction between strands.

The digital recordings of the LF signal from the magnetic test of damaged rope were used to conduct its noise analysis. It was done to prove that the proposed method could be used for the determination of the length of lay in working ropes. The results are presented graphically in Fig. 10 which shows the power spectral density of two superimposed LF signal recordings. One was done in the area of rope damage while the other was done away from the damage on an undamaged part of the same rope. It was obvious that the IWRC and internal rope strands have failed as a result of excessive torque forces. In normal conditions the forces involved would be dissipated as a result of relative movement of strands and wires (moving stress wave) but in this case the relative movement of the internal strands appeared to be arrested. The reason for the latter was believed to be rope internal corrosion, wear, and lack of lubricant resulting in high friction between strands. The results obtained for the undamaged part of the rope allow for easy identification of the basic frequency bands typical for this rope. Some dilution of both the f_2 bands is evident, the result of the progressing wear of the rope, in this case its corrosion and nicking.

The results of noise analysis for the damaged part of the rope indicate existence of significant shifts in frequency bands generated by the internal strands. In particular the band f_{1I} is visibly shifted towards higher frequencies, a clear indication of shortening of the lay length of the internal strands.

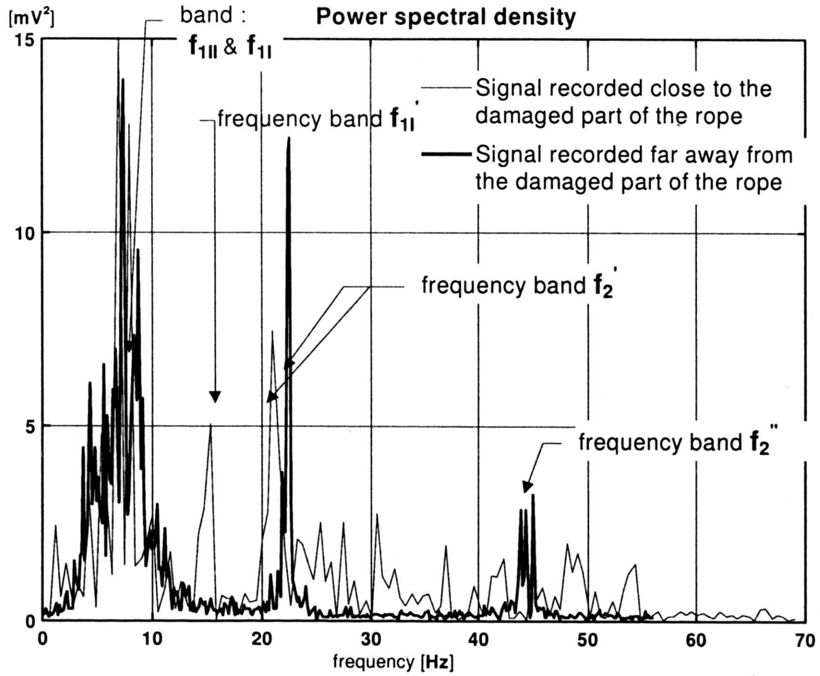

FIGURE 10. Noise analysis of the LF signal recorded during magnetic examination of the failed Cassidy rope; f [Hz] denotes the observed frequency bands.

Its frequency of 14 Hz corresponds to the lay length of 75 mm, or one half of the corresponding lay length in an undamaged part of the rope. The frequency of band f_2, related to the lay length of external strands, is 21 Hz. As compared to 22 Hz for the undamaged part of the rope, this insignificant change indicates slight increase of the lay length of the external strands of the rope.

The above findings indicate that the noise analysis of the LF signal can be used to define the length of lay of a rope and its strands. Furthermore, noise analysis can be used as a tool for determining internal condition of non-rotating ropes as related to possible seizure of the internal rope strands.

In reference to the damaged rope a speculation is made that that the movement of the internal strands was arrested due to their relative swell, a result of significant reduction of the lay length. The other factors named above, namely: corrosion, wear and lack of internal lubrication aggravated the problem. During the post-failure magnetic examination of the failed rope a local tightening of internal strands lay length was found to exist in several other parts of the rope, although the reduction was not so severe as in the failed part of the rope.

This failure shows that if the LL analysis were performed earlier the rope installation would be protected against damage.

6. Conclusions

- The signal analysis of the LF signal gives new opportunities in NDT magnetic tests of wire rope.
- LF signal noise analysis can be used to define the actual lay length of wire ropes and rope strands, including the internal rope strands. As such the noise analysis is a useful tool in the assessment condition of multi-strand, non-rotating ropes. It allows the identification of parts of the rope where significant change in the lay length of the internal rope strands takes place and which may be susceptible to the type of failure described in this paper.

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