Research of Wire Rope Damage Identification Techniques using Sensor Fusion

Kenya OHTSUKA†, Akihisa TABATA1, Jun MAEDA1 and Yoshio AOKI1

†Precision Machinery Engineering, Nihon University, 7-24-1 Narashinodai, Funabashi-shi, Chiba, Japan.

1E-mail: cske17008@g.nihon-u.ac.jp

1 Precision Machinery Engineering, Nihon University.

Abstract

In Non-Destructive Testing of wire ropes, the Magnetic Flux Leakage Testing Method is employed using magnetic sensors for damage detection. However, while it is still possible to detect issues when there are various types of damage present, it is hard to define the specific damage types. At present, it is also difficult to detect slight levels of internal damage. This research aims to solve that problem by developing a new method of damage inspection useful to Non-Destructive Testing of wire ropes. This method will use sensor fusion to combine the signals from different sensors for accurate damage identification. The proposed technique uses magnetic sensors, hall effect sensor ICs as well as optical sensors. We believed that by utilizing optical sensors, a difference in the signal patterns between abrasions and rust could be used to identify damage that could not be recognized by magnetic sensors. Also, for the wire rope flaw detector utilizing this technique, we designed an array layout for each sensor type. Sensor fusion was performed by combining the magnetic, optical and linear displacement sensor arrays. In this report, four types of general wire rope damage patterns were prepared for testing: internal breakage, external breakage, rust and wear; the results of the flaw detection testing using the newly developed damage inspection system will be discussed. The results show differing signal patterns for each damage type. This shows that damage patterns can be identified by extracting and processing these differing signal patterns.

Keywords: Sensor Fusion, Wire Rope, Damage Identification, Magnetic Flux Leakage Testing Method, Testing

1 Introduction

Since there are numerous support structures incorporating support structures for wire ropes, used in buildings, bridges and cableways, it becomes necessary to perform inspections and maintenance. ISO states ways to dispose of or replace standard wire ropes, with the current main method being external visual inspection, which can lead to subjective or qualitative judgements. In addition, inspection is increasingly being left to construction managers, who lack experience and knowledge in inspecting wire ropes. Therefore, there are cases where erroneous judgment leads to a serious accident. To solve these problems, a flaw detector for the prevention and safety is under development. The current wire rope flaw detector uses a magnetic sensor array system that implements magnetic flux leakage testing method, to detect breakage, wear and rust in the wire rope. However, when there are multiple types of damage such as internal corrosion or rust that can't be visually seen, it makes it difficult to detect breakage or perform identification of the level of damage. Therefore, the necessity has been pointed out for an inspection system that uses multiple arrayed sensors to detect varying physical properties and make a combined decision about the main points of issue.
In this study, we developed a wire rope flaw detector using sensor fusion with magnetic sensors, as well as two other types. Through identifying the different types and levels of damage through the damage inspection test, we will consider the feasibility for use in rating structure health and in a preventative safety system.

2 Wire Rope Flaw Detector using Sensor Fusion

2.1 Sensor Fusion

Imitating the combination of all senses humans possess into an engineering process is known as sensor fusion. It is very difficult for current technological sensing systems relying on only one type of sensor for information to identify the type and level of damage to the object being measured. If multiple sensors were used, and information was combined, multiple damage types could be identified that one sensor can't achieve. They can also assist in making decisions and providing information on damage levels for accident prevention.

The four things that sensor fusion can bring to the sensing field, is multisensors, integration, fusion and association. Below details each type and their characteristics, with Fig. 1 visualizing the information.

(a) Multisensor
   Process for paralleling data from multiple sensors, or achieving combined complimented outputs
(b) Integration
   Process for achieving data organization by calculation processing information from multiple sensors
(c) Fusion
   Process for achieving a new information perception through the differences in sensor information or between sensor information and internal models
(d) Association
   Process that makes it possible to, when mutual relationships in sensor data are different from what was expected, identify that as an abnormality

Figure 1: Sensor Fusion Categorization
2.2 Wire Rope Flaw Detector

Wire rope flaw detectors used today use magnetic sensors to perform the magnetic flux leakage testing method for inspection of damage. However, it is difficult to perform accurate classification of the damage type. When performing damage type identification, there are two issues to consider when using only magnetic sensors in a wire rope flaw detector.

- Difficult to discriminate the internal and external damage
- Difficult to detect the rust and corrosion

When the distance between strands in internal or external breakage is equal, the () from internal breakage compared with external breakage has a longer period (inverse of frequency). In practice, however, the distance between strands after breakage is not constant, making it difficult to identify the damage from just the peak and period of the internal and external breaks. Also, when inspecting for rust and when corrosion is deep into the wire rope, the magnetic sensors can detect the magnetic flux leakage, however it becomes difficult to detect when the rust is only on the surface, and corrosion has not penetrated deep into the wire. Therefore, we developed a wire rope flaw detector that could identify the type and degree of damage through the use of sensor fusion.

As a wire rope flaw detector that can identify three types of damage (breakage, rust and wear), it was developed to incorporate sensor fusion, by including a magnetic sensor array, optical sensor array and a linear displacement sensor array. Breakage is identified through the magnetic sensors, and as rust can be identified as a reddish discoloration on the surface, the signal from an optical sensor makes it possible to identify it. We also decided a direct contact linear mechanism would be appropriate for identifying wear through a decrease in wire diameter over a wide range. Fig. 2 shows the sensor arrangement of the sensor array relative to the wire rope. Fig. 3 shows the system block for the wire rope flaw detector that was developed, with the detector's cross-section and outer appearance shown in Fig. 4. For this test, a rotary encoder sent the data sensing start signal once every millimeter, and the signal values were recorded. As we were intending for the inspection speed to be 500 mm/s, we developed a system that would be able to sample more than 500 times per millimeter.

![Figure 2: Sensor Arrangement of Sensor Array](image)

(a) Hall Sensor Array   (b) Optical Sensor Array   (c) Linear Displacement Sensor Array

Figure 2: Sensor Arrangement of Sensor Array
3 Measurement Experiment for Each Damage Pattern

3.1 Experiment Method

For the flaw detection test, a wire rope following the Japan Industrial Standards (JIS) 6x24 with a diameter of 9mm was used. Breakage (internal, external), wear and rust damage types were prepared in a wire rope sample which was used in the flaw detection test. Fig. 5 shows sections of the prepared damage types. Also, in order to reduce noise from the wire rope vibrating while being measured, the wire rope flaw detector was fastened to a platform, and the wire rope was fed horizontally through the detector. In order to increase the sensitivity of the magnetic sensor, strong samarium cobalt magnets were fixed to a support stand to magnetize the wire directly before it entered the flaw detector, as shown in Fig. 6.
3.2 Breakage

To represent internal breakage in the 3700 mm long wire rope, 2, 4, 6, and 8 central fibres in the wire were broken every 400 mm from the left. From the right, 2, 4, 6 and 8 strands were broken every 400 mm so that they would represent external breakage.

3.2.1 Results and Discussion

The measured signals during the flaw detection test underwent Continuous Wavelet Transform (CWT) signal processing, with the results shown in Fig. 7. The parameters for CWT are shown in Table 1. Magnetic sensors and optical sensors are non-contact, so even if one sensor records a peak, the other sensors won't be affected. Therefore, 8 signals were integrated and processed. The linear displacement sensors selected are contact-type, meaning that if one sensor detects a peak, the other sensors would display a reverse phase waveform. Thus, it is important not to focus on the integrated data, but to perform parallel fusion of the data for processing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hall</th>
<th>Optical</th>
<th>Linear No.1</th>
<th>Linear No.2</th>
<th>Linear No.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mother Wavelet</td>
<td>Paul</td>
<td>Mexican Hat</td>
<td>Paul</td>
<td>Paul</td>
<td>Paul</td>
</tr>
<tr>
<td>Parameter</td>
<td>10</td>
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<td>10</td>
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</table>

Table 1: Wavelet Parameters of Breakage

If you focus on the magnetic sensor array scalogram shown in Fig. 7, you can see that both internal and external breakage can be accurately identified. However, this still is unable to identify the difference between internal or external breakage. For the answer to this, let us consider the optical sensor array scalogram. We can see for samples after 2000 mm, the outer diameter sees some variation over a wide area, corresponding to where breakage occurs. The same can be seen if we...
examine the linear displacement sensor array scalogram as well. Furthermore, at around 800 mm the optical sensor shows a signal of $200\sim300\times10^{-3}$ [1/mm]. By comparing it with the signal $500\times10^{-3}$ [1/mm] from the external wire breakage, a longer period can be identified. Regarding the inspection of each strand one by one when looking for external breakage, for internal breakage when a strand has ruptured, the strand tends to bulge out. We can see this results in a period with a strand diameter of 3mm. From the above, we have shown that it is possible to identify the difference between internal and external wire breakage when using a collaboration of sensing data.

3.3 Localized Wear

With a 2000 mm wire rope, wear damage was applied to the rope every 400 mm, by decreasing the rope diamater 8 %, 6 %, 4 % and 2 %, and measured through the flaw detection test.

3.3.1 Results and Discussion

Fig. 8 shows the results of processing the measured signals using CWT. Table 2 shows the parameters used for the CWT of the measured signals.

<table>
<thead>
<tr>
<th>Hall Mother Wavelet</th>
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<th>Linear No.1 Parameter</th>
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<tr>
<td>Parameter</td>
<td></td>
<td>8</td>
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</table>

Table 2: Wavelet Parameters of Localized Wear

By focusing on the magnetic sensor array scalogram as shown in Fig. 8, the precise identification of the wear damage locations can be seen. For the mother wavelet of wire breakage using magnetic sensors Paul was used, but since the damage form wear is spreadout, a sharp-peak method like Paul is
insufficient, thus we used Mexican Hat for analysis. Not only did the field of wear damage show low frequencies, but wire breakage also showed up as having high frequencies. By focusing on the optical sensor array scalogram, we can see a variation in the measured value, consistent with that of the magnetic sensor array, but still it is not clear enough for making a decision regarding wire breakage. So, next we need to look at the values shown by the linear displacement sensors. Compared with line breakage, we can see the value varies over a wide range. The No. 3 linear displacement sensor value is very clear, so we know that at location three there is wear damage. Also, the reason we see slight changes in the No. 1 and No. 2 values is due to a reverse phase of the waveform, and by combining these it appears possible to identify regional wear damage.

3.4 Rust

Subsequently, by forcibly corroding a 1700 mm wire rope every 300 mm (100 mm wide corrosion range) at angles of 45, 90, 180 and 360 deg along its outside, we were able to achieve rusting, which we inspected through the flaw detection test.

3.4.1 Results and Discussion

Fig. 9 shows the results of processing the measured signals using CWT. Table 3 shows the parameters used for the CWT of the measured signals.

<table>
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<tr>
<th>Mother Wavelet</th>
<th>Hall</th>
<th>Optical</th>
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<th>Linear No.2</th>
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Table 3: Wavelet Parameters of Rust

Figure 9: Wavelet Scalogram of Rust
Let us focus on the optical sensor array scalogram as shown in Fig. 9. As rust was induced, we can see that the optical sensors accurately identify the damaged locations. Also, from the scalogram we can see that even the magnetic sensors are displaying some response. This means that it could be possible to identify the depth of corrosion, as the magnetic sensors are also able to identify rust. This means that by incorporating sensor fusion, we can also identify whether the damage is due to rust or wire breakage.

4 Conclusion

By developing a wire rope flaw detector incorporating a combined sensor array, we verified that through utilizing sensor fusion and signal processing techniques, the capability of wire rope flaw detection can be increased. Especially, the extent of damage, position and type have all been shown to be identifiable. Furthermore, by processing data to draw out characteristics of signal patterns, a more exact identification of damage position, recognition of damage combinations and prediction of how damage may develop can be achieved.

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References