A comprehensive study of the magnetic concentrating sensor for the damage detection of steel wire ropes

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Abstract
Magnetic flux leakage (MFL) method is an important way to detect the fault of steel wire ropes and the sensor for the collection of MFL plays a vital role in the damage detection. Among varied sensors based on MFL method, the magnetic concentrating sensor shows a lot of advantages in the detection of wire ropes. The use of the magnetic concentrator can assist the magnetic sensitive component to detect the MFL and reduce the number of the Hall components. The lift-off of the magnetic concentrating sensor can also be set to a feasible value which is easier to be ensured in the practical application.

Although many researches on the magnetic concentrating sensor have been carried out, few of them have a comprehensive and thorough investigation, which should include the simulation analysis, the prototype design, the broken wire experiment and the comparison with other commonly used sensors. In this paper, a magnetic concentrating sensor is developed and compared with a Hall array sensor through both simulation and experiments. Firstly, the three-dimensional models of the magnetic concentrating sensor and the Hall array sensor are designed and their performance on collecting MFL is analyzed through finite element method (FEM). Secondly, the prototypes of the two kinds of sensors are designed according to the simulation results and their corresponding processing circuits are made. Finally, the effectiveness of the two sensors is evaluated by broken wire experiments with different rope diameters. The simulation and experimental results demonstrate that the magnetic concentrating sensor achieves a higher sensitivity and signal-to-noise ratio (SNR) than the Hall array sensor with less Hall components and simpler pre-processing circuit.

1. Introduction

Thanks to the advantages of high strength, light weight and good flexibility, steel wire ropes are widely used in industrial and civil constructions, such as mine hoisting, bridge suspension elements and elevators [1–3]. As most of the steel wire ropes are load-bearing components and exposed to the external environment directly, the ropes will inevitably generate various damages, which become potentially dangerous in the production [4]. In order to avoid accidents, many organizations and institutions use visual inspection to detect the rope. The method, however, takes a lot of time and only the external damage can be observed. Some organizations will replace the steel wire ropes regularly, but most of the ropes that have been replaced are still in service, which causes a huge material waste [5]. Therefore, it is necessary to develop a device to detect the faults of steel wire ropes effectively and enhance the safety of its operation.

Among many nondestructive testing methods, electromagnetic testing is the most widely used in the damage detection of steel wire rope, and magnetic flux leakage (MFL) method is the most effective way to detect broken wires [6–9]. In the past few decades, many scholars have designed damage detection sensor of wire ropes based on MFL principle [10–14]. Kim et al [10] designed a Hall array sensor for the local defects inspection of wire ropes. Support vector machine (SVM) and Hilbert transform-based enveloping method are applied to diagnose the defects. Li et al [11] uses Hall array sensor to detect the axial damage of steel wire rope. The quantitative size
of the defects is analyzed through binarizing local grey value of the MFL data. Singh et al [13] designed the GMR-based MFL sensor to inspect the faults of the wire rope. The experimental results show that the GMR sensor can identify 2 mm-deep axial and circumferential notches and resolve flaws separated by a distance of more than 3.2 mm. Wu et al [14] applied tunnel magneto-resistive element to the MFL sensor. The TMR-based MFL sensor is used for detecting a flaw of a single broken wire with a diameter of 0.5 mm, and the induced MFL signal can be clearly recognized from the oscillation signal.

Whether the MFL generated by the defects of the wire rope can be completely collected is an important principle for the sensor design. The Hall array sensor employs a circle of Hall components to collect the whole MFL, but the circuit processing becomes complex due to the excessive use of Hall components. The sensitivity of the magneto-resistance sensor to the MFL is higher, but the lift-off should be the micron level, which is difficult to be ensured in the actual detection due to the inevitably fluctuation of the wire rope in the sensor.

The magnetic concentrating sensor collects the MFL through the magnetic concentrator, and leads it into the magnetic sensitive component, which makes it easier for the magnetic sensitive component to collect the MFL. Because of the existence of the magnetic concentrator, only a few magnetic sensitive components are needed to make a comprehensive collection of the MFL, which simplifies the structure of the sensor and reduces the difficulty of signal processing [15–17]. Kang et al [15] analyzed the principle of magnetic concentration and evaluated the effectiveness of the magnetic concentrator through a mathematical model. The size of the concentrator is given for the wire ropes with different diameters. Wang et al [16] designed various models of the concentrator and studied the detection effect of each model through the finite element method (FEM). The structure of the magnetic concentrator which is suitable for collecting the MFL is demonstrated by the theoretical and experimental results.

However, very few literatures designed the prototypes of both the magnetic concentrating sensor and the traditional Hall array sensor and compared their performance of fault detection. In this study, the performance of the magnetic concentrating sensor and the Hall array sensor on concentrating MFL is analyzed through FEM. Then, we designed the two kinds of sensors and applied them to broken wire experiments with different rope diameters. Their detection effect is compared and discussed by the experimental results.

The rest of the paper is organized as follows. Section 2 describes the basic theory of MFL method and magnetic concentrating detection. In section 3, the performance of the magnetic concentrating sensor and the Hall array sensor is analyzed by FEM. Section 4 details the examination of the effectiveness of the two sensors through broken wire experiments. Finally, the conclusions are drawn in section 5.

2. Theoretical background

2.1. MFL principle

Figure 1 shows the detection principle of the magnetic flux leakage (MFL). The wire rope is a ferromagnetic component, which is easy to be magnetized by the magnet. The yoke is also a material with good magnetic conductivity. Part of the rope in the sensor is magnetized by a permanent magnet and the whole sensor forms a closed magnetic circuit. When the wire rope is intact, the flux is almost inside the wire rope, as shown in figure 1(a). When a defect occurs, the steel wire at the damaged position will have a fracture. As the permeability of the air is very small and the magnetic resistance at the damage position increases, there will be leakage of magnetic flux, as shown in figure 1(b). The magnetic sensitive component placed close to the surface of the wire rope can sense the MFL and the damage can be detected.
2.2. Principle of magnetic concentration

The principle of the magnetic concentrating detection is illustrated in figure 2. A single Hall sensor collects a component of the spatial MFL. Adding concentrators on both sides of the magnetic sensitive component can help it collect the MFL. Since the concentrator is usually made of materials with high permeability and the MFL will preferentially pass through the position with high permeability, the MFL will be collected by the concentrator more easily. The magnetic sensitive component is placed in the middle of the concentrator, so that the MFL collected by the concentrator will be imported into the magnetic sensitive component.

A Hall component is adopted to collect the spatial MFL, and its output voltage is given by the following expression:

\[
V_{HH} = K_{HH} I_C \int_S B_z(x, y, z) d_x d_y = K_{HH} I_C \Phi_1(x, y, z),
\]

Where \(K_{HH}\) is a constant, which is decided by the characteristics of the Hall component; The current and the sensing area of the Hall component are \(I_C\) and \(S_{HH}\), respectively. When the \(K_{HH}\) and the current \(I_C\) are constant, the output voltage \(V_{HH}\) is directly related to the sensing area \(S_{HH}\) according to Formula (1).

Adding magnetic concentrator with size of \(l \times w \times h\) on both sides of the magnetic sensitive element. The magnetic flux \(F_1\) collected by the concentrator can be calculated as follows:

\[
F_1(x, y, z) = \int_S B_z(x, y, z) d_x d_y d_z,
\]

In the equation (2), \(S_1\) is the collecting surface of the magnetic concentrators parallel to the XOZ plane. The \(S_1\) is much larger than the sensing surface \(S_{HH}\) of the Hall component. If the magnetic flux \(\Phi_1\) collected by the concentrator is completely sensed by the Hall component, the Hall output voltage will increase accordingly, which will improve the detection effect of the MFL sensor.

3. Finite element analysis of the two sensors

The finite element method (FEM) is one of the most widely methods for the simulation of magnetic field [18–20]. In the paper, the three-dimensional model of the magnetic concentrating sensor and the Hall array sensor are established and their performance on collecting MFL is analyzed through FEM.

3.1. Model establishment

The size of the designed magnetic concentrator [16] is illustrated in figure 3. The concentrator consists of two magnetic collecting rings and two magnetic bridges. The concentrator and Hall component cooperate to collect the MFL. The permeability of the concentrator is hundreds or even thousands of times of the air, and the MFL will be more easily collected by the concentrator. As shown in the figure 3, the magnetic flux collected by one side of the magnetic collecting ring will pass through the magnetic bridge to the other side of the magnetic collecting ring. The Hall component is embedded on the magnetic bridge. The cross-sectional area of the bridge is almost the same as the sensing area of the Hall element, so that most of the MFL collected by the magnetic collecting rings can be imported in the Hall component. This structure only needs a few Hall components to realize the comprehensive collection of the MFL. In order to eliminate the strand noise, the length of the magnetic collecting ring \(l\) should be one half of the strand distance of the wire rope [15]. Since the sensor is designed for the rope type of 24 mm diameter, the length \(l\) is 12 mm, and the thickness \(\Delta h\) of the magnetic bridge is 2 mm. The internal and external diameter parameters \(D_i\) and \(d_i\) of the magnetic collecting ring are decided according to the lift-off, as given in table 1.
The overall model of the magnetic concentrating sensor and the Hall array sensor are displayed in figure 4. The steel wire rope with a diameter of 24 mm is established seven steel strands and a $2 \times 2 \times 2$ mm fracture is made on the rope. As presented in figures 4(a), 12 Hall components are arranged at the detection position of the Hall array sensor. The size of the magnetic concentrating sensor is described in figure 4(b). Two magnetic collecting rings are set at the detection position and two Hall components are placed on two magnetic bridges.

3.2. Simulation result

Two kinds of sensors are simulated with and without fracture respectively and the difference of magnetic flux density of every Hall component is obtained. The sum of the differences between the 12 Hall components of the Hall array sensor and the sum of the differences between the 2 Hall components of the magnetic concentrating sensor are calculated and compared. The result is shown in figure 5.

In the figure 5, the black square represents the situation of Hall array sensor and the red circle illustrates the result of the magnetic concentrating sensor. The abscissa represents the lift-off and the ordinate is the sum of the difference of the magnetic flux density of Hall components in the sensor. It can be seen from the figure that after the steel wire rope is damaged, the difference of the magnetic flux density of the Hall components in the magnetic concentrating sensor is bigger than that of the Hall array sensor. In addition, with the increase of lift-off, the difference of the magnetic flux density of the two sensors will decrease. However, the downward trend of the magnetic concentrating sensor is obviously smaller than the Hall array sensor. These differences reflect the performance of the sensor to collect the MFL, which indicates that the effect of detecting the damage of the steel wire rope is better by using the magnetic concentrating sensor.

Moreover, whether the Hall array sensor or magnetic concentrating sensor is used in the steel wire rope detection, the smaller the lift-off, the better the detection effect. In engineering application, the wire rope cannot be guaranteed to be in the axial center of the sensor. A fluctuation is usually around 2–3 mm [21, 22]. Therefore, the lift-off of both sensors is designed to be 4 mm and correspondingly $D_1 = 42$ mm, $d_1 = 32$ mm.
4. Experiment and discussion

4.1. The magnetic concentrating sensor and the hall array sensor

The magnetic concentrating sensor designed in this paper is illustrated in figure 6(a). The magnet NdFeB35 is used to magnetize the test rope and the yoke is used as the magnetic conducting path. The concentrator is embedded in the middle position of the sensor. The magnetic concentrator consists of two magnetic collecting rings, where each ring has a magnetic bridge and each magnetic bridge has a Hall component. The magnet, yoke and concentrator are all embedded in nylon bushing. There are guide wheels on the outside of the sensor to make the tested rope in the axial center of the sensor during the detection process. As shown in figure 6(b), a printed circuit board (PCB) is developed for the pre-processing of the output signal of the sensor. There are two sliding rheostats on the PCB, which can adjust the output of the Hall component to zero when there is no damage to make it easier for the Hall component to sense the MFL.

The designed Hall array sensor is shown in figure 7(a). Its excitation structure and overall size are the same as the magnetic concentrating sensor. Instead of the magnetic concentrator, a Hall array composed of 12 Hall components is employed to collect the MFL. The Hall components are clamped on the nylon bushing by the lining buckle. Its preprocessing PCB, shown in figure 7(b), is much more complex than the PCB of the magnetic concentrating sensor. When there is no damage, it will take a lot of time to zero the output voltage of Hall components.

The signal acquisition system is presented in figure 8. The output of the sensor is preprocessed through the designed circuit board and then connected to a NI PXI-4496 card for the analog-digital conversion. A LabVIEW acquisition program is developed to control the hardware and display the output voltage of the sensors in real time.

Figure 5. Magnetic flux density of the Hall component with different lift-off.

Figure 6. Prototype of the magnetic concentrating sensor: (a) The sensor; (b) The printed circuit board.
4.2. Experimental Process
The two sensors are used in the broken wires inspection of the steel wire rope with different diameters. A 6 × 37 + FC wire rope with a diameter of 24 mm and a 6 × 37 + FC wire rope with a diameter of 22 mm are taken as damaged specimens, and their wire diameters are 1.1 mm and 1.0 mm respectively. As shown in figure 9, five broken wires are made on the surface of each wire rope and separated by a distance of 250 mm. The number of the broken wires is 1–5 respectively and the length of the fracture of each broken wire is 12 mm.

The broken wire experiments are carried out on the steel wire rope testing rig. As displayed in figure 10, the test rig contains aluminum frame, fixed part and loading part. The damaged rope is placed on the test rig for the inspection. The rope is fixed on the experimental platform through the rope buckles and kept parallel to the ground. The loading device can realize loading of 0–30 tons to simulate the actual working state of the steel wire rope. The sensor is fastened on the rope and fixed by two plugs. The mobile pallet drives the sensor to move along the wire rope and detect the damage. During the experimental process, the moving speed of the sensor is 0.25 m sec⁻¹.

4.3. Experimental results and analysis
The damage ropes were detected by the magnetic concentrating sensor and the Hall array sensor respectively. Figure 11 presents the experimental results of the rope with a diameter of 24 mm, and the lift-off is 4 mm. The
The abscissa axis is the distance of the movement of the sensor and the ordinate axis represents the amplitude of the signal voltage (V). The red dotted line represents the damage signal obtained by the magnetic concentrating sensor, and the blue solid line is the detection signal of the Hall array sensor. As can be seen from the figure, the signals received by the two sensors have five saltation. The position of each saltation corresponds to the location of each broken wire, which indicates that both sensors have detected the MFL signals of broken wires on the damaged rope. The baseline of the two groups of signals is almost the same. Nevertheless, the voltage amplitude of the magnetic concentrating sensor is larger than the Hall array sensor and the signal-to-noise ratio (SNR) of the MFL signal of the magnetic concentrating sensor is higher than the signal of the Hall array sensor, which shows that the performance of damage detection using the magnetic concentrating sensor is better than that of the Hall array sensor. The result is consistent with the simulation in section 3.2.

The experimental results of the wire rope with a diameter of 22 mm is shown in figure 12. Similarly, the red line shows the damage signal of the magnetic concentrating sensor, and the blue line is the detection signal of the Hall array sensor. The lift-off becomes 5 mm due to the decrease of diameter of the wire rope. As the lift-off increases, the amplitudes of MFL signal of both sensors decreases. The changes of MFL signals of two kinds of sensors are shown in table 2. Obviously, the MFL signals detecting by the magnetic concentrating sensor has a smaller reduction compared with the Hall array sensor, which verifies the above conclusion.

5. Conclusions

In this paper, the magnetic concentrating sensor is comprehensively studied to inspect the damage of steel wire ropes. The sensor uses a concentrator to assist the Hall component to collect the MFL caused by the faults. We designed the magnetic concentrating sensor and a Hall array sensor and studied their damage detecting effect through both simulation and experiment. The simulation results show that the magnetic concentrating sensor
can collect the MFL produced by the damage more effectively, and is not easily affected by the lift-off. The effectiveness of the proposed sensor is verified through wire breaking experiments with different rope diameters. The Hall array sensor is used as a comparison. The experimental results show that the MFL signal measured by the magnetic concentrating sensor has larger amplitude and higher SNR than the Hall array sensor. When the lift-off becomes larger, the downward trend of MFL signal collected by the magnetic concentrating sensor is smaller than the Hall array sensor, which verifies the simulation results. At the same time, only two Hall components are needed in the magnetic concentrating sensor to collect the MFL, which greatly simplifies the complexity of subsequent signal processing.

Although it is complicated to process the signal of the Hall array sensor, the signal may contain more information than that of the magnetic concentrating sensor in some cases. Through the methods of information fusion [23], deep learning [24, 25], transfer learning [26], etc the signals of the multi-sensor of the Hall array sensor may be helpful for the recognition of fault locations. It is meaningful to explore a fault recognition model suitable for processing the damaged signals of the two sensors in the future work.

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Conflicts of interest

The authors declare no conflict of interest.

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