Signal acquisition system for broken wire of elevator wire rope based on TMR sensor

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Abstract: Aiming at the problems of low detection accuracy, large size and quality of the detection equipment, and difficulty in online monitoring in the magnetic flux leakage detection of elevator wire ropes, a broken wire signal acquisition system was built based on the tunnel magnetoresistance sensor TMR2703, and a dual-loop excitation device was designed and simulated to verify. The dipole model determines the detection direction of the sensor, acquires the magnetic flux leakage signal with the signal preprocessing circuit and the differential detection ring, develops the host computer in LabVIEW, displays the broken wire signal waveform in real time, and stores the collected data in the form of TDMS files, completed the feature extraction of broken wire signals. Experiments show that the system can collect the magnetic flux leakage signal of the wire rope in real time, and can accurately extract the characteristic value of the magnetic flux leakage signal with different numbers of broken wires. The peak value, valley value, peak-to-peak value and signal wave width of the signal have an increase with the number of broken wires. The law of increase can be used to judge the damage degree of the wire rope according to the detection waveform.

1. Introduction

Steel wire ropes are critical lifting and traction components in elevator systems. Because of its bad working environment, it is easy to be damaged in the process of work, such as broken wire, wear, corrosion and deformation, which has a great potential safety hazard. Therefore, it needs to be detected timely and effectively\textsuperscript{[1]}. At present, magnetic flux leakage (MFL) method is widely used in wire rope detection. Many scholars have carried out various detection methods based on the principle of MFL\textsuperscript{[2–3]}, but there are still some shortcomings, such as low detection accuracy, large volume and mass of detection equipment, and difficulty in on-line monitoring. Besides, most of the current research is based on traditional Hall sensors. The influence of sensor layout on the detection results was not analyzed. In order to solve the above problems, this paper proposes a detection method based on TMR2703 sensor, designs a dual loop excitation structure and verifies its magnetization effect by simulation, establishes a magnetic dipole model to determine the detection direction of the sensor, and transmits the sensor output.
signal to the upper computer through the preprocessing circuit and acquisition equipment. The broken wire signal waveform and related characteristic values of the tested wire rope are obtained.

2. Experimental plan

2.1 Leakage magnetic detection principle and excitation structure design
Magnetic flux leakage testing method first needs to excite steel wire ropes, and the excitation methods mainly include AC magnetization, DC magnetization and permanent magnet magnetization. The permanent magnet magnetization device has been widely used because of its light weight, small volume, stable magnetization effect and low detection cost, the principle shown in Fig.1.

![Fig.1 Principle of permanent magnet detection for wire rope defects](image1)

When the external magnetic field acts on the ferromagnetic material, high-density magnetic lines of force will be formed inside the wire rope. If there is broken wire on the surface or inside, the magnetic resistance will increase, and part of the magnetic lines of force will overflow outward to form a magnetic leakage field, and the damage information of the wire rope can be retrieved by analyzing the signal, so as to achieve the purpose of quantitative detection of broken wire of the wire rope. The magnetic circuits generated by the wire rope under different excitation circuits will directly affect the integrity of the wire rope broken wire signal. Single loop magnetization is susceptible to the diameter of the steel wire rope and the unilateral suction, the detection accuracy is low and the structure is unstable, and the disadvantage of the ring magnetization is that the processing process and installation are more troublesome, so this article is designed as shown in Fig.2(a). The magnetization model, and in the finite element simulation software Maxwell replaces the wire rope with a 6mm solid steel rod to obtain the magnetic density cloud map shown in Fig.2(b), the excitation effect of such a structure is verified.

![Fig.2 Double circuit magnetization structure](image2)

In Fig.2 (a), the armature has a size of 50mm * 6mm, a thickness of 10mm, and the permanent magnet is a rare earth permanent magnet having excellent magnetization capacity, a size of 15 mm * 15mm, a thickness of 10mm, and a gas gap value of 1mm. Fig.2 (b) shows that the designed excitation structure forms a long uniform magnetization section of the steel wire, which has a length of about 35 mm, and an analog fracture produces a stable drain magnetic field, which can be acquired by a magnetic sensor. The direction of detecting the sensor installation is an important factor affecting the results of the detection result. The method of establishing a magnetic dipole model to determine the mounting
direction of the sensor, the equivalent magnetic dipole model can be used to indicate the leakage information of the fracture end[6], as shown in Fig.3:

![Magnetic dipole model](image)

Fig.3 Magnetic dipole model

Assume that there is a pair of equivalent of the magnetic dipole $P_1, P_2$, the electric charge is $Q$, and the fracture width is $2l$, the distances from point $A(x,y)$ to magnetic dipoles are $r_1, r_2$, magnetic field superposition theorem indicates that the magnetic induction at $A(x,y)$ is equal to the vector sum of the magnetic induction generated by the point magnetic charges $P_1$ and $P_2$, the penetration factor $\alpha_s$ is introduced to represent the penetration ability of the magnetic leakage field at the damage site, to reduce the influence of the strand structure of the wire rope and improve the accuracy of the model, the axial magnetic induction intensity $B_x$ at $A(x,y)$ is:

$$B_x = \frac{Q\alpha_s}{4\pi\mu_0} \left[ \frac{x-l}{\left[ y^2 + (x-l)^2 \right]^\frac{3}{2}} - \frac{x+l}{\left[ y^2 + (x+l)^2 \right]^\frac{3}{2}} \right]$$

(1)

Similarly, the radial magnetic induction intensity $B_y$ at $A(x,y)$ is:

$$B_y = \frac{Q\alpha_s}{4\pi\mu_0} \left[ \frac{y}{\left[ y^2 + (x-l)^2 \right]^\frac{3}{2}} - \frac{y}{\left[ y^2 + (x+l)^2 \right]^\frac{3}{2}} \right]$$

(2)

In the formula, $\mu_0 = 4\times10^{-7} \text{ H/m}$ is the magnetic permeability of the vacuum. Calculation and analysis by magnetic circuit theory $\alpha_s$, and Setting the extraction distance $y$ and the fracture width $2l$ as the fixed value, this point of the magnetic field axial and radial components are related to $x$-related functions.

When $y=2\text{mm}$, $l$ is set to 0.5mm, 0.8mm, 1.1mm, 1.1mm, 1.4mm, and 1.7mm, At point $A(x,y)$, the distribution law of the axial direction and radial magnetic field is shown in Fig.4:

![Deficiency leakage magnetic field radial component and axial component](image)

Fig.4 Deficiency leakage magnetic field radial component and axial component
Fig. 4 (a) shows that the radial component of the lack of leakage magnetic field is between the defect center, the peak spacing is equal to the fracture width, and the comparison Fig. 4 (b) may be seen that when the extraction distance $y$ and the fracture width $2l$, the same time, the radial component amplitude of the lack of leakage magnetic field is much higher than the axial component, so the sensor should set the detection direction to obtain a larger drain magnetic field strength.

### 2.2 Pretreatment circuit

The detection sensor element is TMR2703, TMR sensor element has the advantages of low power, high sensitivity, and wide range of linearity compared to conventional Hall sensors. When the external magnetic field varies perpendicular to the surface of the chip, the DC operating voltage is applied, and the TMR sensor provides a differential voltage output to the subsequent signal processing circuit. In order to fully detect the wire rope broken wire damage, it is necessary to detect the entire circumference of the wire rope, and a single TMR sensor is limited, therefore, 8 TMR2703 are arranged along the circumferential direction of the wire rope to form a detection ring, and the signals of each TMR element are superimposed together, which can eliminate the interference of strand wave signal to a certain extent.

The detection circuit design of a single TMR sensor is shown in Fig. 5:

![Fig. 5 Single TMR sensor detection circuit design](image)

In Fig. 5, a decoupling capacitor $C_1$ is connected between VCC and GND to filter high-frequency signals, and TMR2703 outputs differential voltages $V_{\text{out}+}$ and $V_{\text{out}-}$. Firstly, a low-pass filter circuit composed of $R_1$, $C_2$, $R_2$ and $C_3$ filters out part of noise. The cut-off frequency of the circuit is calculated by the following formula:

$$f = \frac{1}{2\pi RC}$$

The value of $R_1$ and $R_2$ in the design is $1.5 \, \mu\Omega$, $C_2$, and $C_3$ value of $100nF$, calculated that the cutoff frequency is about $1061.6Hz$. The OP AMP in the pre-processing circuit is OP07, OP07 is a low noise bipolar operational amplifier IC, which has the characteristics of very low input offset voltage and high open-loop gain. This characteristic makes OP07 very suitable for amplifying weak signal of sensor[7].

The filtered voltage is output to the differential to single ended circuit module, which converts the differential voltage of TMR output to single ended output, so as to amplify the output voltage of multiple TMR, and obtain the damage of broken wire on the section. When detecting, there will be interference signals from the surrounding environment, so the superposition of signals on a detection ring cannot completely eliminate the influence of strand wave signals[8]. In order to reduce its influence on the detection system and detection accuracy, a differential circuit is designed to realize common mode suppression of interference signals and improve detection accuracy. The TMR array addition circuit and differential circuit are shown in Fig. 6:
Fig. 6  Reverse and differential circuit

Taking $R_f$ as 10 times of $R_1$ in Fig.6(a), the output $U_A$ is:

$$U_A = \frac{R_f}{R_1}(U_1 + U_2 + \cdots + U_8) \quad (4)$$

$U_1 - U_8$ are the filtered output voltage of TMR2703, $R_d$ is the bias resistor, and the resistance value is:

$$R_d = \frac{R_f}{R_1} / R_2 / R_3 / \cdots R_8 \quad (5)$$

In Fig.6(b), connect the outputs $U_A$ and $U_B$ of the two rows of TMR element detection loops to the forward and reverse input terminals of the op amp, and set $R_f/R_1 = R_f/R_2$, and take the resistance value of $R_f$ and $R_1$ equal, then the circuit output is:

$$U = \frac{R_f}{R_1}(U_A - U_B) \quad (6)$$

The differential detection ring shown in Fig.7 is designed to achieve common mode suppression and improve detection efficiency.

Fig. 7  TMR differential detection ring

In Fig.7, the spacing setting of the A and B detection loops must ensure that the entire detector needs to be in the wire rope magnetization uniform region, and the electromagnetic interference formed between the two rings is avoided, so that the pitch L should be set to 35mm.

2.3 Wire wire string signal acquisition system based on LabVIEW

Art-USB2884 data acquisition card is used in the signal acquisition equipment for broken wire of wire rope, and USB data interface can realize high-speed reading and writing of signal. VI in LabVIEW is used to develop upper computer to realize acquisition, storage and feature extraction of different damage signals of elevator wire rope. The data acquisition program is shown in Fig.8
The program of Fig.8 mainly completes the opening / closing acquisition card and configuring the sampling frequency, trigger mode, range, and trigger sensitivity, setting the number of acquisition channels, and setting other parameters according to the actual detection environment. On the basis of realizing the functions of real-time monitoring and control, the acquisition system also needs to store the signal waveform. The binary file TDMS provided by LabVIEW has fast reading and writing speed and small space occupation, which is suitable for multi-channel, long-time and continuous mass data storage[9], so TDMS file is used for data storage. Similar to other file IO functions, need to open, write and close files when using TDMS API. The related procedures are shown in Fig.9:

Wire rope broken wire detection is affected by many factors. Only the peak value of the waveform cannot accurately determine the number of broken wires in a wire rope. Therefore, a program for extracting broken wire signal features is designed to help the subsequent quantitative identification of broken wires. Extract part of the signal segment from the original signal, and extract its peak value, peak-to-peak value, wave width, and waveform area. The Peak Detector function in LabVIEW can obtain the Peak Value and Valley Value of the damage signal waveform. At the same time, it can obtain the characteristic signal peak-to-peak value of the broken wire defect as:

$$V = |\text{PeakValue} - \text{ValleyValue}|$$  \hspace{1cm} (7)
Set a threshold \( V_y \) in the collected broken wire signal waveform interface, regardless of the waveform phase, the damage signal is approximately a sinusoidal signal, as shown in Fig.10:

\[
y = \sin \varphi x
\]

(8)

The waveform width is \( x_2-x_1 \), then \( \varphi = \frac{T}{\pi} \), the sine formula of the damage signal is:

\[
y = \sin \frac{T}{\pi} x
\]

(9)

The waveform area can be acquired on the damage signal in \((x_1-x_2)\), set to \( \Delta S \):

\[
\Delta S = \int_{x_1}^{x_2} \sin \frac{T}{\pi} x dx = \frac{\pi}{T} (\cos \frac{T}{\pi} x_2 - \cos \frac{T}{\pi} x_1)
\]

(10)

According to the above formula, the feature extraction program design of the broken wire damage signal is shown in the fig.11:

![Feature extraction procedure](image)

Fig.11  Feature extraction procedure

After designing the data acquisition module, the TDMS data save module and feature extraction module, the resulting upper machine interface is shown in the Fig.12:
3. Results and Analysis
The experimental sample uses 6x19+FC wire rope with a diameter of 10mm, and it is worn artificially. The magnetic flux leakage signal detected by this system is smoothed by S-G, and the image obtained is shown in Fig.13. It can be found that the signal acquisition system of wire rope broken wire based on TMR sensor can detect the magnetic flux leakage, and the signal is relatively stable.

Fig.13 shows that there is a small amplitude fluctuation similar to sine wave in the detection waveform. Through experimental research and analysis, it is considered that this kind of fluctuation is caused by the magnetic field between the strands of the wire rope. For the tested wire rope, four damages with the number of broken wires of 1, 2, 3 and 4 are set in advance, and the characteristic values of different number of broken wires are obtained as shown in Tab.1:
Tab.1  Different broken wire quantity characteristic table

| Number of broken wires | Peak value /mV | Valley value /mV | Peak to peak /mV | Wave width |
|------------------------|----------------|-----------------|-----------------|-----------|
| 1                      | 4256.36        | 4156.26         | 100.01          | 18.31     |
| 2                      | 4280.59        | 4171.33         | 109.26          | 25.09     |
| 3                      | 4292.01        | 4174.90         | 115.11          | 34.11     |
| 4                      | 4372.42        | 4250.77         | 121.65          | 45.76     |

Tab.1 shows that the signal peak, valley, peak value, and signal wave width have increased variations in the increase of the number of filaments, so it can be generally judged from the degree of damage to the wire rope according to the detection waveform.

4. Conclusion

Wire rope detecting devices are designed based on leakage magnetic detection, including dual-loop excitation structures, pretreatment circuits, and TMR sensor array ring. Finite element simulation shows that the double-circuit excitation structure has a good magnetization effect, and the structure is simple and easy to implement. The new magnetic sensor TMR2703 is used instead of the traditional Hall element, and the detection accuracy is improved. The detection of the sensor is determined in the magnetic dipole model. The direction is radial arrangement.

Based on LabVIEW, the wire rope break signal acquisition system realized real-time monitoring of wire rope operating conditions, and realized high-speed storage of signals, solving the problem of online detection of wire rope, and the system can extract different broken wires corresponding to the characteristic value. The quantitative recognition algorithm study of the subsequent wire rope is laid the foundation.

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