Research on crack monitoring technology of multilayer structure based on TMR-eddy current sensor

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Abstract. The flexible eddy current array sensor has the characteristics of flexibility, bendability and light weight, which has a great application prospect in the field of structural health monitoring. The traditional flexible eddy current array sensor is affected by the skin effect and the crack monitoring depth is relatively low. This paper proposes an eddy current array sensor which uses TMR (tunnel magneto-resistance) sensor as sensing channels. It reduces the excitation frequency and increases the eddy current skin depth. The TMR sensor realizes the quantitative monitoring of cracks by the array arrangement. First, the finite element model of the sensor is established, and the influence of the cracks on the different layers of the multilayer structure on the magnetic induction intensity at the test point is analyzed. The simulation and results show that when the crack passes through the sensor, the magnetic induction intensity at the three test points changes in sequence and gradually increases to the maximum value. The direct relative position of the maximum value of the three test points is approximately the same as the distance among the test points. Then, the simulated crack growth experiment of the corresponding sensor is carried out. The experimental results show that as the crack grows, the signals of the three TMR sensors on the eddy current sensor change in sequence, and the distance between the characteristic points is consistent with the distance between the TMR sensors. The output voltage of the sensor decreases with the crack depth increases. The experimental results are consistent with the simulation results, which further verifies the correctness of the simulation model.

1. Introduction
Metal structure is an important load-bearing structure of equipment, and its safety determines the normal operation of the entire equipment. However, the structure is affected by the extremely complex environment during the service process, which can easily cause damage to the metal structure, such as corrosion and fatigue cracks. These all seriously endanger the safe service of the structure. Therefore, in order to ensure the safe service of the structure, non-destructive testing of the structure is required on a regular basis. Conventional non-destructive testing techniques mainly include ultrasonic testing ultrasonic testing (UT)\textsuperscript{[1-3]}, magnetic particle testing (MT), eddy current testing (ET)\textsuperscript{[4]}, radiographic testing (RT)\textsuperscript{[5]} and penetrant testing (PT). Ultrasonic monitoring has a good imaging effect and can detect deep cracks. However, ultrasonic detection technology needs to use coupling agent in the application process, which cannot detect cracks inside multi-layer structures. At the same time, the detection of surface cracks has blind spots. Magnetic particle detection technology can detect the appearance of damage, but this detection technology can only detect ferromagnetic materials and is not suitable for non-ferromagnetic materials such as aluminum alloys. Penetration detection
technology can effectively detect small cracks, but it is not suitable for the detection of internal cracks. X-ray detection technology can effectively detect the occurrence of cracks, but during the detection process, X-rays are more harmful to the human body. Eddy current detection technology has high sensitivity to crack detection, but it is affected by the skin effect, and the crack detection depth is affected by the excitation frequency. The high excitation frequency can only detect the initiation and propagation of cracks on the surface.

As a kind of eddy current sensor, flexible eddy current array sensor has excellent characteristics such as flexibility, bendability, light weight, etc., and has great application prospects in the field of structural health monitoring. Many researchers have conducted in-depth research on it\[6-10\].

However, in order to ensure the signal-to-noise ratio, the flexible eddy current array sensor has a high exciting frequency. Affected by the skin effect, the sensor can only monitor surface cracks. In order to solve the eddy current sensor's ability to detect internal cracks, many researchers replaced the original sensing channels with magneto-resistive sensors, and increased the sensor's crack monitoring depth by reducing the excitation frequency.

Therefore, this paper aims at the problem of multi-layer structure crack monitoring. By replacing the sensing unit of the traditional flexible eddy current array sensor with a TMR sensor, the output signal of the TMR sensor is not affected by the excitation frequency of the sensor. Therefore, the excitation frequency can be reduced and the crack monitoring depth of the sensor can be improved. The finite element model of the sensor is established, and 3 test points are set to analyze the change of the magnetic induction intensity at the test points during the crack propagation process. Then, the corresponding sensor is prepared according to the simulated size, and the simulated crack growth experiment is carried out to verify that the sensor has the ability to quantitatively monitor deep cracks.

2. Flexible eddy current sensor based on TMR sensor

2.1. Sensor structure
The flexible eddy current array sensor based on the TMR sensor is mainly composed of an excitation coil and TMR sensors. The excitation coils has three turns coils in the same direction. The TMR sensor is located at three equidistant positions on the sensor. The specific schematic diagram is shown in Figure 1.

![Figure 1 Schematic diagram of TMR-eddy current sensor](image)

According to Figure 1, the sensitive axis direction of the TMR sensor is along the y-axis direction, the length of the excitation coil along the y-axis direction is greater than the length along the x-axis direction, the length in the y-axis direction is 60mm, and the length in the x-axis direction is 25mm.
2.2. **Principle of Crack Monitoring**

The principle of crack monitoring of eddy current sensor based on TMR sensor is similar to that of traditional eddy current sensor. By applying the excitation coil with drive current, the energized excitation coil generates an alternating magnetic field in space. When the sensor is close to a metal conductor, an eddy current is generated on the surface of the metal conductor which is approximately opposite to the direction of the excitation current. If the crack does not occur, the flow direction of the eddy current will not change, and the magnetic induction intensity at the test point will not change. When cracks are generated and propagated, the flow of eddy currents is affected by the cracks, deviating from the original flow trajectory to form disturbed eddy current, and then affect the output voltage of the TMR sensor. The generation and propagation of cracks are judged by the change of the output voltage of the TMR sensor. The schematic diagram of the eddy current disturbed is shown in Figure 2.

![Figure 2 Schematic diagram of eddy current disturbance on cracks](image)

According to Figure 2, the excitation coil along the y-axis direction generates magnetic fields in the x-axis and z-axis directions in space, and the excitation coil along the x-axis direction generates y-axis and z-axis magnetic fields in space. The direction of the sensitive axis of the TMR sensor is along the y-axis. Therefore, only the magnetic field generated in the space by the excitation coil segment along the x-axis will affect the output signal of the TMR sensor. Since the upper and lower excitation line segments along the x-axis direction are symmetrically distributed with respect to the TMR sensor, and the excitation current flows in opposite directions, the magnetic induction intensity along the y-axis direction generated at the TMR sensor is zero.

When a crack occurs, as shown in Figure 2, the eddy current flows along the surface of the crack. The flow direction of the disturbed eddy current on the upper and lower parts of the crack is opposite and the longitudinal distance from the TMR sensor is not equal. Therefore, a disturbed magnetic field must be generated at the TMR sensor. According to change in the output voltage of the sensor can judge the growth of the crack. Since the TMR sensors are arranged at equal intervals, the crack growth can be judged according to the change trend and sequence of the output signals of different TMR sensors during the crack growth process.

3. **Simulation analysis**

In order to verify the principle of crack monitoring, simulation analysis is carried out in this section. The finite element model of the sensor and the tested structure is established using COMSOL software, and the trend graph of the magnetic induction intensity change at the test point during the crack propagation process is analyzed. Because the TMR sensor is a linear Magnetic field sensor, the output voltage is proportional to the magnetic induction intensity at the test point. Therefore, in the simulation, the change trend of the magnetic induction intensity at the test point can be tested to judge the crack propagation process.
3.1. Sensor simulation model

The three-dimensional finite element model of the sensor and the crack is established by COMSOL finite element software. The measured metal structure is a multi-layer structure. The structure is composed of 3 layers of 2mm aluminum alloy plates. The cracks are set on different layers and the cracks are controlled. The growth of the length is used to simulate the propagation process of the crack. The simulation diagram is shown in the Figure 3.

![Simulation Diagram](image)

Figure 3 Schematic diagram of sensor simulation

3.2. Sensor simulation model

Since the center of the sensor is placed at the origin, the post-processing function of the COMSOL software calculates the change trend of the magnetic induction intensity at the test point with the crack growth.

For when the excitation frequency is 0.5 kHz, the output response curve of the sensor is shown in Figure 4 at different longitudinal distances between the crack and the TMR sensor during the crack propagation process.

![Output Response Curves](image)

Figure 4 Surface crack propagation on magnetic induction intensity at the test point
(a) Test point 1; (b) Test point 2; (c) Test point 3
According to Figure 4, as the longitudinal distance between the test point and the crack increases, the change in the magnetic induction intensity first increases and then decreases. When \( d \) is 2.5mm, the magnetic induction intensity changes at the three test points during the crack propagation process are the largest. When the crack is located on the middle layer and the bottom metal plate, the influence of the crack propagation on the change of the magnetic induction intensity of the test point is shown in Figure 5 and Figure 6.

Figure 5 2mm deep crack propagation on magnetic induction intensity at the test point
(a) Test point 1; (b) Test point 2; (c) Test point 3
3.3. Analysis of simulation results

According to Figure 4-Figure 6, as the longitudinal position between the crack and the test point increases, the change in the magnetic induction intensity at the test point first increases and then decreases during the crack propagation process. For the surface cracks monitoring, when the $d$ is 2.5mm, the amount of change is the largest. For the monitoring of crack propagation in medium layer structure, when $d$ is 5mm, the magnetic induction intensity change at the test point is the largest. For the monitoring of the crack growth of the underlying structure, when $d$ is 5 or 7.5mm, the change in the magnetic induction intensity at the test point is the largest. Therefore, the sensor can monitor the occur of cracks, and as the distance from the crack to the surface increases, the change in the magnetic induction intensity at the test point by the crack propagation gradually decreases. At the same time, at the same depth from the surface of the crack, when the crack expands from left to right to the vicinity of test point 1, the change in magnetic induction at test point 1 reaches the maximum, while the change in magnetic induction at test point 2 and test point 3. The amount is still increasing. When the crack propagates to the vicinity of test point 2, the magnetic induction intensity change at test point 2 reaches the maximum, the magnetic induction intensity of test point 1 reaches a balanced state, and the magnetic induction intensity change at test point 3 is still rising. As the crack continues to grow, the changes in the magnetic induction intensity of the three test points have reached a balanced state, so the maximum value of the magnetic induction intensity changes in the three test points can be used to judge the crack growth and realize the quantitative monitoring of the crack growth.

4. Experimental verification

In order to verify that the sensor has the ability to quantitatively monitor deep cracks, this paper prepares the corresponding sensor according to the simulation size of the sensor. Then, it controls the TMR-eddy current sensor and the multilayer metal structure with pre-crack relative motion to simulate crack propagation.

4.1. Experimental system

The experimental system consists of a TMR-eddy current sensor, metal plate with prefabricated cracks, tow metal plates with no pre-crack, three-axis displacement platform, signal source, power amplifier module, a signal conditioning module, and a self-developed signal acquisition and processing system. The schematic diagram of the connection between each functional module, as shown in Figure 7.
Figure 7 System connection diagram

The multi-layer test piece is composed of three flat test pieces. One of the test pieces is pre-cracked and the other two test pieces are intact. By placing the pre-cracked plate on different layers, the propagation process of crack at different layers can be realized, as shown in Figure 8. The experimental site is shown in Figure 10.

(a) The crack is on the top layer; (b) The crack is on the medium layer; (c) The crack is on the bottom layer

During the experiment, referring to the conclusion of the simulation analysis in section 3.3, when the longitudinal position between the test point and the crack is 5mm, the change of the magnetic induction intensity of the test point by the crack propagation is the largest. Therefore, during the experiment, the longitudinal distance $d$ between the TMR sensor and the crack is 5mm, as shown in Figure 9. The experimental site is shown in Figure 10.
In this paper, the relative amplitude is define as:

\[ R = \frac{V_o}{V_r} = \frac{V_i \cdot k_i}{I_e \cdot R \cdot k_2} \]

Where, \( V_o \) is the output of the sensor. \( V_r \) is sampling voltage, and \( I_e \) is the amplitude of excitation current. \( R \) is the sampling resistor. \( k_i \) is voltage amplification factor of channel \( i \). \( k_2 \) is amplification factor of sampling voltage.

4.2. Experimental results
During the experiment, the effect of different excitation frequencies on crack monitoring was studied. This article uses a multi-frequency excitation method, the applied frequency is 0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz and 5 kHz sine wave composed of synthetic waves. When the crack passes through the excitation coil, the corresponding curve of the sensor's relative amplitude variation for crack identification is as shown in Figure 11-Figure 13.
Figure 11 Magnetic induction intensity variation at the test point with surface crack propagation
(a) Channel 1; (b) Channel 2; (c) Channel 3

Figure 12 Magnetic induction intensity variation at the test point with 2mm deep crack propagation
(a) Channel 1; (b) Channel 2; (c) Channel 3
4.3. Result analysis
Eddy current sensor on cracks on different layer structures is analyzed, and it is found that for the monitoring of surface cracks, the amplitude of the TMR output voltage changes the most. As the crack depth increases, the relative amplitude of the output signal of the TMR sensor begins to decrease. For the monitoring of surface cracks, when the crack propagates to the vicinity of channel point 1, the relative output voltage change of channel 1 reaches the peak value, and the relative output voltage change of channel 2 and channel 3 at this time begins to increase. When the crack grows approaching channel 2, the relative voltage amplitude change of channel 1 begins to slowly decrease, while the relative voltage change of channel 2 begins to reach the first peak, while the relative voltage change of channel 3 is gradually increasing. When the crack extends to channel 3, the relative voltage amplitude change curve of channel 3 reaches the first fixed point. Therefore, the sensor can quantitatively monitor the crack growth, and the crack monitoring accuracy is approximately equal to the phase distance between the TMR sensors.

For the monitoring of surface cracks, as the excitation frequency increases, the relative voltage amplitude variation of each channel gradually increases. For the monitoring of the crack propagation in the middle layer, as the excitation frequency increases, the maximum value of each channel is 0.5 kHz or 1 kHz. At this time, the relative voltage amplitude change of the channel output is relatively large. As the excitation frequency increases, the relative voltage amplitude change of each channel output of the sensor gradually decreases.

5. Conclusions
This paper replaces the original induction coil with TMR sensor, then, it increases the crack monitoring depth of the sensor by reducing the frequency, and adopts the TMR sensor array
arrangement. It realizes the quantitative monitoring of the crack growth of the sensor through the response sequence of the TMR sensor. Through simulation analysis and experiment verification, some conclusions are drawn as the following:

1. The magnetic field component of the y-axis can be measured by the TMR sensor, which can effectively monitor the disturbed magnetic field caused by the crack.

2. The array arrangement of TMR sensors can effectively monitor the growth of cracks.

3. For surface crack monitoring, the higher the excitation frequency, the better the crack identification effect. As the depth of the crack from the surface increases, the crack detection effect can be improved by reducing the excitation frequency.

This research can effectively monitor the crack propagation process on different layers, and the research results provide a certain reference for deep crack monitoring.

Acknowledgements
The investigations in this paper are supported by National Natural Science Foundation for the Youth of China (52007197).

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