

Fusion Gradient Imaging Independent of Crack Orientation Based on MFL and ACFM

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Magnetic Flux Leakage (MFL) and Alternating Current Field Measurement (ACFM) are widely employed techniques for detecting defects in steel. However, their detection performance is often influenced by the orientation of the cracks, which is difficult to predict in real-world inspection scenarios. To overcome this challenge, we propose a novel fusion gradient imaging method. This approach involves scanning the defect along two orthogonal directions, combining the results, and computing the gradient to generate a fused magnetic map that is independent of crack orientation. Through both simulations and experiments on cracks with various orientations, we demonstrate that the proposed method effectively determines the position and orientation of surface cracks. The fusion gradient imaging technique ensures accurate and reliable crack detection, representing a significant advancement in electromagnetic non-destructive testing for surface crack inspection.

Index Terms—Alternating current field measurement (ACFM), magnetic flux leakage (MFL), fusion gradient imaging, tunneling magnetoresistive (TMR)

I. INTRODUCTION

DETECTION of surface defects in steel, especially in railway tracks, is crucial for ensuring safety and preventing track failure[1, 2]. In many kinds of NDT techniques[3], Electromagnetic testing offers high sensitivity, efficiency, low cost, and non-contact detection, making it an ideal method for detecting surface and near-surface defects in steel. Electromagnetic testing is primarily based on two principles: Magnetic Flux Leakage (MFL) [4] and Alternating Current Field Measurement (ACFM)[5]. However, both methods have a critical dependency on defect orientation. MFL is particularly sensitive to cracks that are perpendicular to the magnetic field, making it more effective for detecting vertical cracks in ferromagnetic materials. In contrast, ACFM is sensitive to cracks parallel to the magnetic field, making it more suitable for detecting horizontal cracks. Due to this directional sensitivity, relying on only one of these methods can lead to inconsistent or incomplete defect detection when the orientation of the crack is unknown. This paper proposes a fusion gradient imaging method that combines MFL and ACFM, fusing scanned magnetic maps from two orthogonal directions to eliminate the influence of crack orientation.

II. NUMERICAL SIMULATION

This paper uses the AC/DC module of COMSOL to create a finite element simulation model for the detection module and the crack, as shown in Fig 1. The air domain consists of a spherical space and an external infinite domain. The coil is wound around the U-shaped magnetic core, positioned near the test sample's surface, with the defect located at the center. A fine subdomain with small mesh sizes is defined near the defect for accuracy.

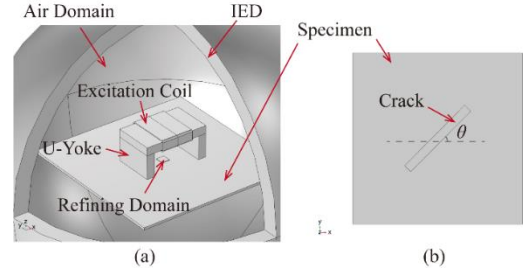


Fig. 1. (a) Schematic diagram of the simulation model, (b) Schematic diagram of the crack orientation.

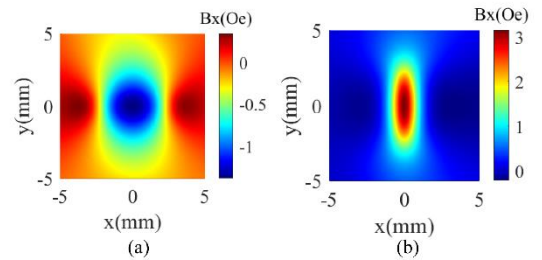


Fig. 2. Magnetic field component map in the x-direction obtained from the simulation when the crack extends along the (a) x-axis and (b) y-axis.

When a current flows through the excitation coil, it generates a magnetic field that is conducted through the magnetic core to the surface and near-surface regions of the steel sample. In ferromagnetic materials like steel, cracks cause two types of magnetic field disturbances. The first is magnetic flux leakage (MFL), where the magnetic field leaks out at the crack site. The second disturbance is from surface currents induced by the alternating magnetic field, where the crack causes change in the current's direction leading to an uneven magnetic field above the defect. The relative contributions of these two effects depend on the crack orientation. Despite the crack's constant

size, the magnetic field distribution's shape and amplitude change significantly with the crack's orientation.

III. FUSION GRADIENT IMAGING

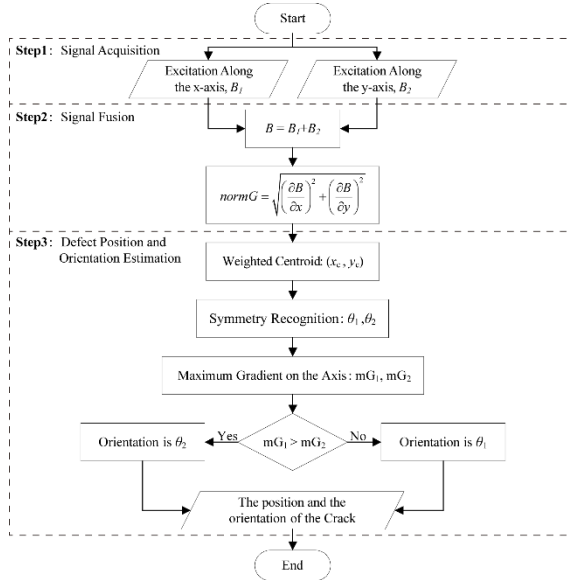


Fig. 3. Flowchart of the Fusion Gradient Imaging Method.

Some published works have addressed the issue of crack orientation by introducing rotating excitation fields[6, 7], but these methods are complex in structure and suffer from low signal-to-noise ratio (SNR). This paper proposes a fusion gradient method to reduce the impact of crack orientation. The method involves two scans in orthogonal magnetic field directions, followed by the fusion of the resulting magnetic field maps. Regardless of the crack orientation, the fused magnetic field map retains sufficient leakage and electric field disturbance information. Calculating the gradient distribution of the fused magnetic map further helps identify the crack's features. Using this method, we can determine the defect's position and orientation, as shown in Fig 3. The feasibility of this method is validated through simulation results, as shown in Fig 4.

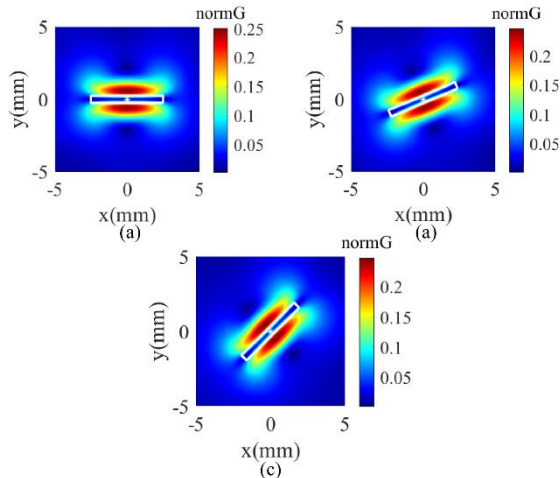


Fig. 4. The fusion gradient images obtained from the simulation for crack orientations of (a) 0°, (b) 22.5°, and (c) 45°, with the white boxes indicating the estimated crack positions and angles.

IV. EXPERIMENTAL SETUP

The schematic diagram of the electromagnetic system is shown in Fig 5. The test sample is placed on a fixed desktop stand, while the detection probe, consisting of an excitation coil, a U-shaped magnetic yoke, a TMR magnetic sensor, and a 3D enclosure, is mounted on an XYZ motion platform. A computer-controlled signal generator provides excitation current to the coil. The TMR output signal is amplified and filtered by the PCB circuit. The processed signal is then acquired by the data acquisition card and transmitted to the computer. After each acquisition, the computer controls the XYZ motion platform to move the probe to the next sampling point. The experiment can yield results similar to the simulation.

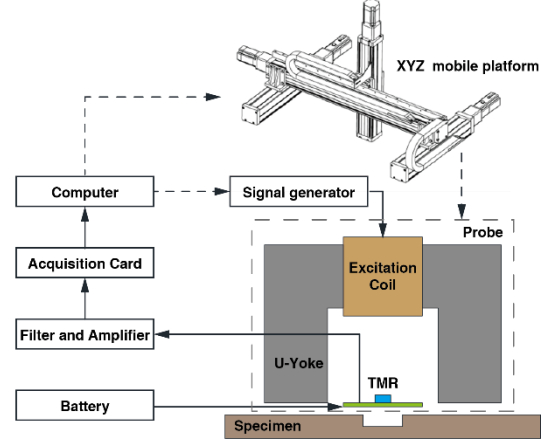


Fig. 5. Schematic diagram of the experimental setup.

V. CONCLUSION

This study proposes a fusion gradient imaging method for detecting surface and near-surface cracks in iron, aimed at eliminating the influence of defect orientation and providing accurate visualization of surface defects. Simulation and experimental results demonstrate the feasibility of the method. Future work will focus on research into curve feature inversion algorithms and expanding the application of the method to various defect types and materials for broader non-destructive testing applications.

REFERENCES

- [1] B. Feng, J. Wu, H. Tu, J. Tang, and Y. Kang, "A review of magnetic flux leakage nondestructive testing," *Materials*, vol. 15, no. 20, p. 7362, 2022.
- [2] M. P. Papaelias, C. Roberts, C. Davis, M. Lugg, and M. Smith, "Detection and quantification of rail contact fatigue cracks in rails using ACFM technology," *Insight-Non-Destructive Testing and Condition Monitoring*, vol. 50, no. 7, pp. 364-368, 2008.
- [3] D. S. Ing and J. Li, "Railway Defect Detection Method: A Review," *CONSTRUCTION*, vol. 2, no. 2, pp. 22-30, 2022.
- [4] A. I. B. M. N. Muhamad, "Study of Magnetic Tunnel Junction based Gradiometric Sensor for Magnetic Flux Leakage Testing," *Tohoku University*, 2022.
- [5] P. Xu, Y. Chen, L. Liu, and B. Liu, "Study on high-speed rail defect detection methods based on ECT, MFL testing and ACFM," *Measurement*, vol. 206, p. 112213, 2023.
- [6] W. Li, G. Chen, J. Ge, X. Yin, and K. Li, "High sensitivity rotating alternating current field measurement for arbitrary-angle underwater cracks," *Ndt & E International*, vol. 79, pp. 123-131, 2016.
- [7] C. Ye, Y. Huang, L. Udpa, and S. S. Udpa, "Differential sensor measurement with rotating current excitation for evaluating multilayer structures," *IEEE Sensors Journal*, vol. 16, no. 3, pp. 782-789, 2015.