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Influence of metallic shields on pulsed eddy current sensor for ferromagnetic materials defect detection

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ABSTRACT

Pulsed eddy current (PEC) with transient analysis is a significant advance over conventional eddy current testing using impedance analysis at a particular frequency. The fabrication and optimization of PEC sensor are important issues in PEC applications in nondestructive testing (NDT) field especially for ferromagnetic materials. In this work, the influence of metallic shields on circular PEC sensor for defect detectability in ferromagnetic metals has been investigated through finite element models (FEM) and experimental studies by comparing iron and aluminum shields with no-shield. Both simulations and experiments indicate that PEC probe with an aluminium shield can effectively enhance the amplitude of PEC response in both surface and subsurface defect detection. However, the sensitivity is decreased. In contrast, iron shield has better shielded performance and can effectively improve the sensitivity of both surface and subsurface defects detection in ferromagnetic materials.

1. Introduction

As one of the advanced electromagnetic nondestructive testing (NDT) technologies, pulsed eddy current (PEC) has a lot of advantages over eddy current testing (ECT) [1,2] and other NDT methods. Comparing to conventional ECT, PEC's frequency spectra are wider and information is richer, thus it can be used to detect defects at different depths at the same time. And, various features extracted from time and frequency domains (such as peak time, rising time and frequency to zero) can be used to estimate sizes, locations and types of defects [3]. Unlike ultrasonic, PEC does not require couplant and is totally non-contact. Contrary to optical methods which only detect surface damages, PEC can inspect inside of the material due to electromagnetic filed diffusion. Lastly, PEC does not have any radiation and it is environment friendly. Due to these advantages, PEC has been used in material characterization, geometry measurement and defect detection for these kinds of materials: (1) non-ferromagnetic metal and its alloy, such as aluminum and copper slabs and multi-ply structure in aircraft; (2) ferromagnetic materials [4–9], such as steel corrosion characterization and assessment of wall thinning in insulated ferromagnetic pipes [10,11]; (3) conductive composites, such as carbon fiber reinforced plastic (CFRP) and sandwich honeycomb structures [12]. In these applications, the fabrication and optimization of PEC sensor, the analysis and feature extraction of PEC sensor signal are the important issues. By now, a lot of works are focused on sensor design of PEC and other electromagnetic NDT.

The PEC probe usually comprises a driving unit for magnetic field excitation and sensors for magnetic field measurement. The driving unit is normally an induction coil in either cylindrical or rectangular shape [13]. The sensors for magnetic field measurement are usually bobbin coil or magnetic sensor. For non-ferromagnetic metal and conductive composites, more attention has been paid on structural design and feature extraction [14]. However, ferromagnetic material is special due to the great permeability. Due to electric conductivity and the iron magnetic field resulting from magnetic permeability, the induced magnetic field in the ferromagnetic material is the superposition of eddy current (EC) induced magnetic field [15]. There is a significant difference in PEC sensor signals between ferromagnetic and non-ferromagnetic materials. Therefore, not only PEC sensor but also other EM NDT such as magnetic flux leakage (MFL) sensor should be optimized for ferromagnetic material detection. On the basis of the analysis of magnetic refraction, Sun et al. [16–20] put forward a new principle of MFL based on magnetic vacuum leakage, in which the strong

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background magnetic field is eliminated. Song [21] reported that detection signals of EC probe are integrating MFL and EC signals on the saturation magnetization state. For the ferromagnetic metals, the PEC will magnetize the ferromagnetic sample at the same time. Therefore, PEC probe can detect defects based on the leakage of magnetic flux and eddy current. On the other hand, the remote field eddy current (RFEC) has been applied for the inspection of the conducting tubular products such as oil and gas pipes [22–24]. Shijn [25] reported the progress in designing a shielded encircling RFEC probe to inspect nuclear fuel rods and investigated resulting signal characteristics. These results show that the totally shielded probe dramatically improved signal characteristic. H. WANG [26] designed a new RFEC transducer for inspection of flat conductive plates with shielding structures. The results of numerical simulations and experimental study indicate that the new transducer has the capability of detecting deep buried defects. In order to eliminate the disturbance of the background magnetic field, the technology of shielding was put forward to obtain the disturbed field preferably above the defect. The above studies indicate that the technique shields play important roles in MFL and RFEC.

The motivation of this work is explained as follows. According to the state-of-the-art review of sensor of PEC and other Electromagnetic NDT including EC, MFL, and RFEC for ferromagnetic materials, it can be found that detection signals of PEC are complex and irregular because of eddy current magnetization of ferromagnetic metal, and the shielding technology can remarkably improve the sensor performances. However, the influence of the metallic shield on the PEC sensor for defects detectability in ferromagnetic metals has not been investigated. Furthermore, as explained in [27], non-ferrite metallic material (shields) will reduce the quality factors of eddy current sensor and ferrite metallic material (shields) will increase the quality factors, high permeability material in particular. Therefore, different metallic shields will have different behaviors of PEC. This work is devoted to solve this problem. The lift-off is commonly known to be one of the main obstacles for effective eddy current NDT testing, which can disturb the response signals and lead to the erroneous results, as the same in PEC testing. However, this paper is focused on investigating the influences with the different shield structure of PEC probes without considering the influences of variable lift-off. And, this work has not considered the defect detection with big lift-off in the 2–5 cm range, because this is the preliminary study. The big lift-off will be investigated in the next work. Finite element models (FEMs) and experimental studies are conducted to investigate the PEC sensor with aluminum and iron shields and no-shield for defect detection in ferromagnetic materials. The rest of the paper is organized as follows. Firstly, simulation studies are conducted in Section 2. Then, the PEC experimental system is built in Section 3, which is followed by experimental studies and discussion in Section 4. Finally, the conclusion and future work are outlined.

2. Simulations with FEM

2.1. Simulation setup

A 2D axis-symmetric model of the cylindrical PEC probe has been established using COMSOL Multiphysics 4.3b [28]. The physical field was selected as magnetic field under AC/DC module and then solved using the transient solver. In an effort to investigate the influence of shield on defect detectability in ferromagnetic metals, three models were established, which are: 1) without a shield (with no-shield); 2) with iron shielding; and 3) aluminum shielding. The PEC sensor model without shield is shown in Fig. 1(a), while the models with iron and aluminum shields are presented in Fig. 1(b). The simulation parameters were set as follows: the excited current (in square waveform) was set with maximum amplitude of 0.5A, excitation frequency of 100 Hz. The turns of coil are 667 and the cross-sectional area of enameled wire is 1 mm^2. The inner diameter, outside diameter and height of the PEC probe are 20 mm, 30 mm and 20 mm, respectively. The iron plate was selected as a sample with electrical conductivity of 1.12×10^7 S/m and relative permeability of 4000, thickness of 10 mm. Material settings of the shielding are iron and aluminum, respectively. The relative permeability and conductivity of aluminum are 1 and 3.77×10^7 S/m, respectively. The relative permeability and conductivity of iron are 4000 and 1.12×10^7 S/m, respectively. The shield is 1 mm thick, 10 mm high and 5 mm wide. In the actual situation, the gap exists between the specimen and shield, and the distance was set to 0.05 mm in the simulation. Because of the dimension of the probe and the built-in Hall sensor in the shield, 1 mm of thickness is more suitable for the investigation.

2.2. Distribution of eddy currents and magnetic field

The distributions of eddy currents and magnetic field induced by PEC sensor were observed under no-shield, iron and aluminum shields. The current density and magnetic induction lines were acquired through the solution. Fig. 2(a)–(c) show the distribution of

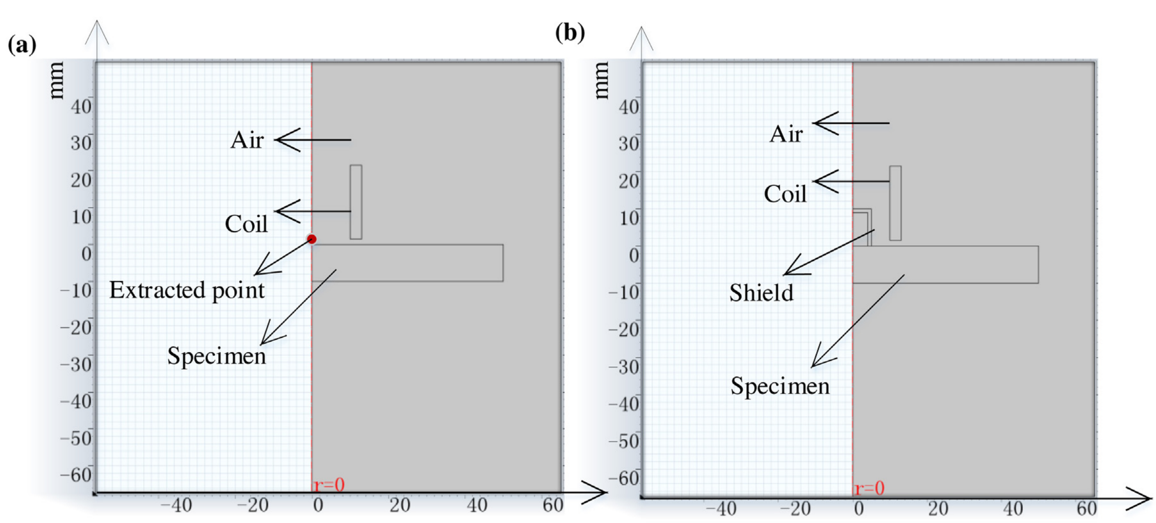

Fig. 1. (a) The model of PEC sensor without shield and (b) with shield.