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Influence of key factors on Eddy current testing sensitivity and monotonicity on subsurface depth for ferromagnetic and non-ferromagnetic materials

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ABSTRACT

Studies on key influencing factors (coil's size and excitation frequency) of eddy current testing (ECT) sensitivity, monotonicity and defect detectability have been carried out for detection of subsurface defects in ferromagnetic and non-ferromagnetic plate materials. A set of ECT finite element models and experiments have been accomplished and the detection performance has been analyzed and compared. The simulation and experiment results have indicated that for ferromagnetic material, the amplitude response of low frequency excitation has lower sensitivity but better monotonicity than high frequency. The phase response of low frequency excitation has higher sensitivity and better monotonicity than high frequency. For the non-ferromagnetic plate material, the lower the excitation frequency is, the smaller the detection sensitivity of the amplitude response is. Outside a defined excitation frequency, the defect monotonicity of the amplitude response reduces. For phase response, the lower the excitation frequency is, the smaller the detection sensitivity and the greater the monotonicity. The coil's size has a certain extent influence on the detection sensitivity. For ferromagnetic and non-ferromagnetic plate materials, it is effective to enhance the detection sensitivity of amplitude response by increasing the size of the exciter coil and the detector coil within a certain range; and it is effective to enhance the detection sensitivity of phase response by decreasing the size of the detector coil or increasing the size of exciter coil within a certain range.

1. Introduction

It is important to carry out periodic nondestructive testing and evaluation (NDT&E) for high-risk equipment. Eddy current (EC) testing, due to various merits including high sensitivity, fast speed, non-contact, low cost, and no requirement of couplant, has been widely adopted. However, it is well known that EC is concentrated on the surface of the material due to skin effect. Therefore, it is generally believed that it is difficult to detect deep defects by EC testing [1].

In order to solve this problem, researchers have carried out a series of studies. The initial approach is to use low-frequency excitation so that EC penetration depth is large. However, low-frequency excitation will reduce the sensor resolution and detection speed, which make this method not suitable for actual detection. Another approach is to adopt a remote field EC technique, which mainly used for the detection of ferromagnetic tubes [2,3]. It has advantages such as almost equal sensitivity to inner and outer defects, and insensitivity to lift-off, but it is hard to detect the flat-panel conductor. In order to realize a remote field zone, where indirect coupling energy is stronger than direct coupling energy, on a flat-panel conductor, the exciter coil and detector coil need to be shielded [4,5]. However, unlike traditional remote field EC detection, it is very difficult to suppress the energy of the direct-coupled channel by the magnetic shielding structure for the detection of flat-panel conductive material, especially when the probe needs to realize real-time scanning detection.

Some researchers have proposed multi- frequency [6–8] or pulse excitation [9–11] to achieve deep defect detection. However, these methods based on the exponential decay of the electromagnetic field inside the conductor are still subject to skin

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effect restrictions. Furthermore, several studies have proposed superimposing several electromagnetic fields [12,13], so that the electromagnetic field inside the conductive material is not exponentially decaying, which is not limited by the skin effect. However, this method requires multiple excitation sources, and the probe is very large, complex and high cost, which makes it not suitable for industrial product testing.

The commonly used EC penetration depth formula is referred to as the standard EC penetration formula, that is, the EC amplitude decays to its initial value of 1/e corresponding to the Eq. (1):

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

where, f is excitation frequency in Hz, μ is the magnetic permeability of the specimen in H/m, σ is the electrical conductivity of the specimen in S/m. Smith R A's study [14,15] has found an important phenomenon: the EC penetration cannot be simply calculated using the above empirical formula, the EC penetration formula should be modified as Eq. (2):

$$\delta = \frac{1}{Re\left[\sqrt{k^2 + j\omega\mu\sigma}\right]} \tag{2}$$

where k represents the spatial angular frequency (mm^{-1}), $\omega = 2\pi f$ is the temporal angular frequency, which is related to the excitation frequency f. According to experimental research, the Eq. (1) is valid only if the spatial frequency is 0 (means the probe size is infinite large. According to Eq. (2), k has little effect on the penetration depth when ω is large. On the contrary, k has a great influence on the penetration depth when ω is small. To sum up, this equation has shown that both coil's size (reciprocal of k) and temporal excitation frequency f have great influence on penetration depth of EC signal. In other words, it decides that if a deep defect can be detected or not using EC testing. We can conclude that the temporal angular frequency has a joint influence with coil's size on detection effect. Thus, both effects of the excitation frequency and coil's size are investigated in this paper.

Inspired by the study of Smith R. A., the objective of this paper is to study the influence of coil's size and excitation frequency on detection sensitivity and monotonicity for different materials through finite element simulation and experimental studies. The detection effect of subsurface defects with different height was evaluated by the amplitude and phase of response signal with different excitation frequencies and different EC probe sizes.

2. Finite element simulation

2.1. The establishment of simulation model

In this study, finite element simulation software COMSOL Multiphysics 5.2 has been used to build the 2D axisymmetric EC model based on reflection electromagnetic wave. Under the alternating current/direct current (AC/DC) module, the physical field was chosen as the magnetic field and the solution was analyzed in the frequency domain. The software module is built on magnetic vector potential (A) and electric scalar potential (V) formulation. It numerically solves the partial differential Eq. (3) governing the EC phenomenon [16]:

$$\nabla \times \left(\frac{1}{\mu}\nabla \times A\right) = -j\sigma\omega A - \sigma\nabla V + J_s \tag{3}$$

Where J_s is the source current density in A/m^2. In this model, the EC probe and the metal specimen enclosed in an external boundary are subjected to Drichlet boundary conditions ($A = 0$) which is commonly used in the axisymmetric outer boundary. Table 1 gives detailed physical parameters in the model, i.e. μ and σ. The exciter coil and the detector coil were set as a multi-turn coil, and their wire diameter was set as 0.3 mm and 0.1 mm, respectively. The conductivity of air sub-domain is set to a non-zero value to avoid computational problems typically encountered during the finite element model solving [17].

Table 1
Detailed parameters of the subdomain in FE model.

S.No.	Material	Conductivity (σ), S/m	Relative magnetic permeability (μ_r)
(1)	Air	10	1
(2)	Q235	7.14×10^6	250
(3)	Al6063	3.03×10^7	1
(4)	Detector coil	6×10^7	1
(5)	Exciter coil	6×10^7	1

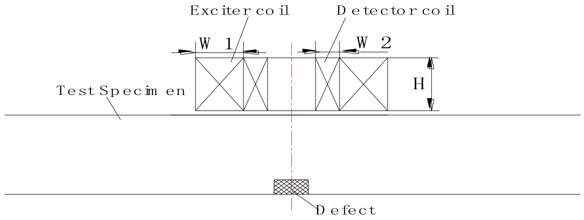

Fig. 1. General schematic of a reflection EC probe.

The coil's size is an investigated parameter in this work. Fig. 1 shows a general schematic of a reflection EC probe, where $W1$ represents the exciter coil thickness in mm, $W2$ is the detector coil thickness in mm, and H is the coil height in mm. In order to reduce the experimental variables, the height of the three coils is uniform, detector coils are all kept inside the exciter coil, and lift-offs are set as 0.5 mm. In order to study the influence of EC probe size on the detection performance, three EC probes numbered (1), (2) and (3) with different sizes were designed. The specific values of parameters for three probes are presented in Table 2. These probes can be divided into two groups: first group with the same detection coil but different excitation coil, second group with the same excitation coil but different detection coil, as shown in Fig. 2(a) and (b), respectively, in order to facilitate comparative analysis.

The excitation frequency is another investigated parameter in this work. The selection of excitation frequency should be considered together with the coil's size. For detection of smaller subsurface defects, lower excitation frequency and larger diameter probe are preferred [16]. However, excessive probe size would result in poor resolution and detection sensitivity. Due to the limitations of the experimental conditions, the smallest inside diameter

Table 2
Dimensions of EC probes in FEM.

S.No.	W2(mm)	W1(mm)	H(mm)
(1)	2	4	4
(2)	2	8	4
(3)	4	8	4

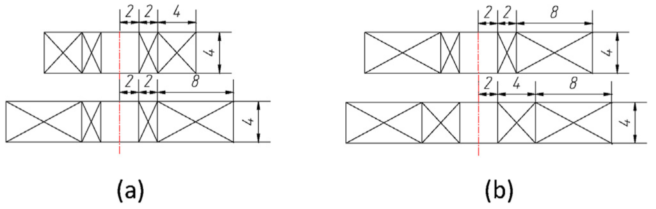

Fig. 2. Comparison of probe size: (a) different size exciter coil with the same size detector coil; (b) different size detector coil with the same size exciter coil.