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Conductivity Lift-off Invariance and measurement of permeability for ferrite metallic plates

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ABSTRACT

In this paper, a Conductivity Invariance Phenomenon with a controlled lift-off is discovered and studied. It is found that at certain lift-off, the effect of conductivity influence on inductance is eliminated/reduced. Based on this phenomenon, a novel permeability measurement approach is proposed. The proposed approach was verified by both simulation and experimental data. And the permeability can be estimated in a reasonable accuracy (with an error of 2.86%) by the proposed approach without the influence of its conductivity.

1. Introduction

Both the electrical conductivity and the magnetic permeability of a measured sample have significant impact on the detected signal in eddy current non-destructive testing (NDT) [1–5]. Therefore, approaches of obtaining accurate measurement for the electrical conductivity or magnetic permeability have been of great interest to design and manufacturing engineers.

In recent years, the eddy current technique (ECT) [6–8] and the alternative current potential drop (ACPD) technique [9–11] are the two primary electromagnetic non-destructive testing techniques for the measurement of metal conductivity and permeability. For the conductivity measurements, several instruments based on eddy current technique at a relatively high frequency (100 Hz-20 kHz) and alternative current potential drop method at a low frequency (1 Hz-100 Hz) were already proposed. These instruments can predict a wide conductivity range of samples. However, majorities of them can only measure the non-ferrous material samples [12,13].

The measurement of permeability is still a challenge due to the influence of conductivity on the measured signal. Therefore, decoupling the impact of the sample's conductivity and permeability is vital in permeability measurement [14]. Some studies have been proposed for the ferrous metallic permeability prediction based on both eddy current technique and alternative current potential drop method [12,15]. However, these methods all use a low excitation frequency (1 Hz-50 Hz), which may reduce the precision of the measurement. Yu has proposed a permeability measurement device based on the conductivity invariance phenomenon (CIP) [16]. And the measured results tested by the device were proved to be accurate. The only imperfection of this device is requiring substrate metal on the top and bottom sides of sample, which is impractical in some applications, for example, in cases where only one side of the sample is accessible. Adewale and Tian have proposed a design of novel PEC probe which would potentially decouple the influence of permeability and conductivity in Pulsed Eddy-Current Measurements (PEC) [18]. They reveal that conductivity effects are prominent in the rising edge of the transient response, while permeability effects dominate in the stable phase of the transient response; this is as we encountered in multi-frequency testing, as the rising edge of the transient response contains high frequency components while the stable phase contains lower frequency components and low frequency is more related to permeability contribution due to magnetisation. They use normalisation to separate these effects.

In this paper, a new Conductivity Invariance Phenomenon is discovered and investigated (as shown in part 2.C), which can tackle the solution uniqueness problem due to the coupling impact of the sample's electrical conductivity and permeability. In addition, the influences of conductivity range, excitation frequency, and metallic plate thickness on the proposed Conductivity Invariance Phenomenon are analysed in part

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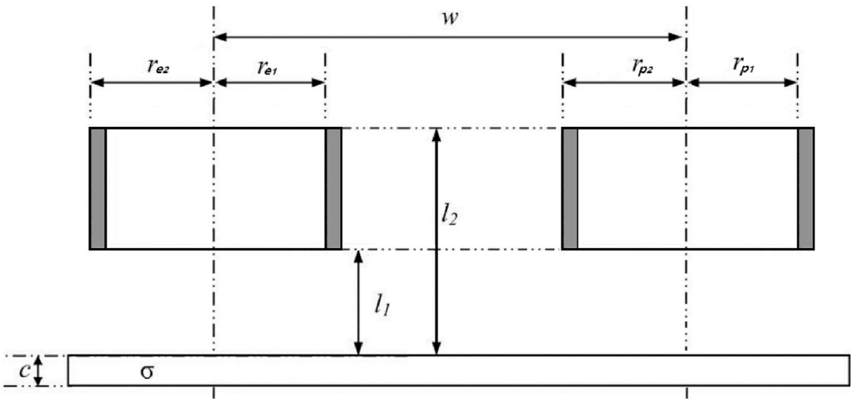

Fig. 1. Front view of sensor configuration.

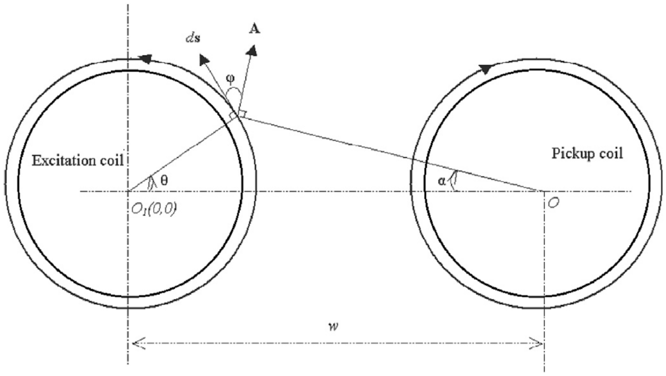

Fig. 2. Top view of sensor configuration.

Table 1
Coil parameters.

Inner radius r_1 (re_1/rp_1)	0.75 mm/ 0.75 mm
Outer radius r_2 (re_2/rp_2)	1 mm/1.25 mm
$r_0 = (r_1 + r_2)/2$ (re_0/rp_0)	0.88 mm/1 mm
w (width between two coils' centre)	3 mm
$le_2 - le_1$ (height of excitation coil)/$lp_2 - lp_1$ (height of pickup coil)	3 mm/3 mm
le_1/le_2 (lift-off)	0–10 mm
Plate thickness c	5 mm
Frequency f	90 kHz
Number of turns N1/N2	160/200

N1 for Exciting coil, N2 for pickup coil

2.D - part 2.F. Finally, a comparison of permeability calculated by different lift-offs (both Conductivity Invariance Lift-off and its neighbours) is presented for the performance of the proposed permeability measurement method (as shown in part 3).

2. Conductivity Invariance Lift-off on non-destructive eddy current tesing

2.1. Air-cored sensor configuration and models

In both numerical simulation and experiments, the tested samples are tin, iron, brass, aluminium and copper with conductivity of 8.7, 10.1, 15.9, 35, 59.8 MS/m at 20°. In these models, the targets were tested under a constant excitation frequency (90 kHz). The width, depth and thickness of all the samples are 20 mm, 20 mm, and 5 mm respectively. In this paper, we choose a sensor with a transmitter and receiver arranged non-axially to test the samples. The reason is only this setup has lift-off invariance point while the conventional co-axial probes sensor does not have this feature.

Since the measured impedance of the coil is complex due to the phase difference between the injected current and induced voltage signals, the inductance as defined is also complex (equation (1)). The change in real part of the inductance represents change in the magnetic flux while the imaginary part represents the loss due to the eddy currents. The complex inductance change can be deduced from the impedance definition as follows:

$$\Delta L = \frac{\Delta Z}{j2\pi f} \tag{1}$$

$$\text{Where,}\quad Z = R_z + j2\pi f L_z \tag{2}$$

In addition, a complex inductance can be regarded as a series of a resistor and an inductor.

The exciting coil and pick-up coil are both on the top of the plate with coordinates of (−1.5, 0, l) mm and (1.5, 0, l) mm respectively (where l denotes the lift-off of probes) as shown in Fig. 1.

Fig. 2 shows the configuration of the sensor. And the parameter is listed in Table 1.

Here, the simulations were computed on ThinkStation P510 platform with Dual Intel Xeon E5-2600 v4 Processor, with 16G RAM. And the experimental data was achieved by Impedance analyser SL 1260.

For the experimental data, the real part of the inductance is defined from the mutual impedance of the transmitter and the receiver coils:

$$\mathrm{Im}(\Delta L) = \mathrm{Im}\left(\frac{Z(f) - Z_{air}(f)}{j2\pi f}\right) \tag{3}$$

$$\mathrm{Re}(\Delta L) = \mathrm{Re}\left(\frac{Z(f) - Z_{air}(f)}{j2\pi f}\right) \tag{4}$$

where $Z(f)$ denotes the impedance of the coil with the presence of samples while $Z_{air}(f)$ is that of the coil in air.

2.2. Analytical solution of inductance

In this section, an analytical solution for a double air-cored sensor is presented, which is based on the Dodd and Deeds method [17] (The Dodd & Deeds method has been proposed over 5 decades ago and cited many hundreds times and is still serving a good analytical solver [19–25]).The difference in the complex inductance is $\Delta L = L - L_A$, where the coil inductance above a plate is L. And L_A is the inductance in