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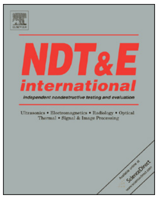

Measurement of lift-off using the relative variation of magnetic flux in pulsed eddy current testing

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A B S T R A C T

Measurement of lift-off can be used to assess the thermal insulation thickness and it has the potential to reduce the lift-off effect in pulsed eddy current testing. In this paper, first, the relative variation of magnetic flux is proposed as a feature for the measurement of lift-off. And then, how to directly obtain the key parameters of the feature from the testing signals is provided. At last, the validity of the feature is verified by simulations and experiments, respectively. The results show that the feature is suitable when the lift-off is tens of millimeters and the plate is ferromagnetic.

1. Introduction

In petrochemical and power generation industries, most of the vessel and pipe are wrapped with thermal insulation to reduce energy loss. The thickness of thermal insulation is an important parameter in installation and maintenance [1]. A pin style apparatus has been employed to measure the thermal insulation thickness to meet quality requirements [2]. The apparatus is a depth gage. To perform a measurement, its pin should stick into the thermal insulation. Hence, the apparatus may be only appropriate for the soft thermal insulation (e.g. rock wool). As for the hard thermal insulation (e.g. foamed glass), which is also widely used in industry, the apparatus will be inappropriate because its pin is hard to stick into. Beside, in the thermal insulation, the pinhole caused by the apparatus could be undesirable. Hence, it is necessary to seek a suitable nondestructive testing (NDT) method for measuring the thermal insulation thickness. When radiographic techniques are used, the measurement may be time-consuming and expensive, because strict protections are required. When ultrasonic techniques are used, it may be difficult to obtain the desirable echo reflected from the surface of metal object that beneath the thermal insulation, because most of the thermal insulation are sound absorbing (e.g. rock wool and foamed glass) and the thicknesses may vary from tens to a few hundred millimeters. When time-harmonic eddy current techniques are used, it may be difficult to obtain a credible result, because time-harmonic eddy current techniques could be mainly used for the measurement of small lift-off, which is no more than several millimeters [3,4]. As an alteration of time-harmonic eddy current techniques, pulsed eddy current testing (PECT), where the coil is excited by a rectangular current, has been used to assess the wall-thinning of metal object without removing the thick thermal insulation [5–8]. The information about the thermal insulation thickness could be contained in the PECT signal and has the potential to be extracted. Therefore, PECT should be more suitable than the above-mentioned approaches, and it will be used to measure the thermal insulation thickness in this paper.

Generally, the thickness of thermal insulation could be considered as the lift-off in PECT because the common thermal insulations are electric insulating. Measurement of lift-off is useful to assess the thermal insulation thickness. Besides, the information about the lift-off and the wall-thinning is hard to be discriminated from the PECT signal. During the assessment of wall-thinning, a constant lift-off is desirable [7,8], while the lift-off is hard to keep constant due to the inevitable installation error and deformation of the thermal insulation. Thus, it suggests the reduction of lift-off effect by measurement of lift-off [8]. There is a feature called LOI slope (the slope of PECT signals at the lift-off point of intersection) could be used to measure the lift-off [9]. However, for the insulated ferromagnetic components, the LOI slope will become unsuitable, because the LOI will not exist when

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the metal object is made of ferromagnetic material and no conductive, non-magnetic material covered [10]. Therefore, it is necessary to propose a suitable feature for these applications.

The typical ferromagnetic PECT signals and features plotted in log–log, semi-log and Cartesian coordinates are shown in Fig. 1a, b and c, respectively. As shown in Fig. 1a, the PECT signal can be divided to early, middle and rear parts by shape. In the early part, an approximate horizontal line and a steep are contained due to the existence and disappearance of the excitation field component [11]. In the middle and the rear parts, the PECT signal decay with time as inverse power and exponential laws, respectively [12]. Some features such as -3 dB point and exponential coefficient obtained [7,12] from Fig. 1a, the slope [5] shown in Fig. 1b, time to peak [6] and the rising point [13] shown in Fig. 1c, are found to assess the thickness of metal object. Those features are obtained from the rear part of the PECT signal. The early and middle parts of the PECT signal have seldom been used. In dual-frequency eddy-current NDE [14], the higher frequency is less sensitive to the thickness of metal object due to the skin effect, and it seems only sensitive to the lift-off. Therefore, the early and middle parts of the PECT signal have the potential to measure the lift-off, because high frequency components can be observed firstly [15]. However, as mentioned above, the early part is related to the excitation field component. Thus, the middle part of the PECT signal is adopted to extract a feature for the measurement of lift-off.

In this paper, a feature for the measurement of lift-off is extracted from the middle part of the PECT signal. The feature is suitable when the lift-off is tens of millimeters and the metal object is made of ferromagnetic material. The rest of this paper is organized as follows. In Section 2, based on the theory analysis of the PECT, the relative variation of magnetic flux is proposed as the feature for the measurement of lift-off. In Section 3, how to directly obtain the key parameters of the feature from the measurement and reference signals is provided based on the evolution of the distribution of eddy current density (ECD), and then the validity of the feature has been preliminarily verified by the simulated signal analysis. In Section 4 an experimental set-up is built to further verify the validity of the feature, and the experimental results are discussed in detail. Finally, a brief conclusion is given in Section 5.

2. Theory

The schematic of PECT is shown in Fig. 2a. Two coaxial coils are situated above a metal plate at a certain lift-off (hereinafter, the lift-off is abbreviated as L). The interior one is a driver coil, and the exterior one is a pickup coil. The driver coil is excited with a rectangular current. At the edge of the rectangular current, eddy currents will be induced in the surface of the metal plate due to the variation of the primary magnetic field (excitation field), and then they will penetrate into the metal plate and attenuate sharply because of Joule dissipation [16]. The transient eddy currents generate a time-varying secondary magnetic field, which is converted to voltage signal by the pickup coil. Recording the voltage signal during the off-time of the rectangular current, the PECT signal will be obtained.

The waveform of the rectangular current is shown in Fig. 2b, where I_0 is the amplitude, and t_1 is the edge time. It is composed of a number of frequency components. Different frequency components have different depths of penetration, because the depth of

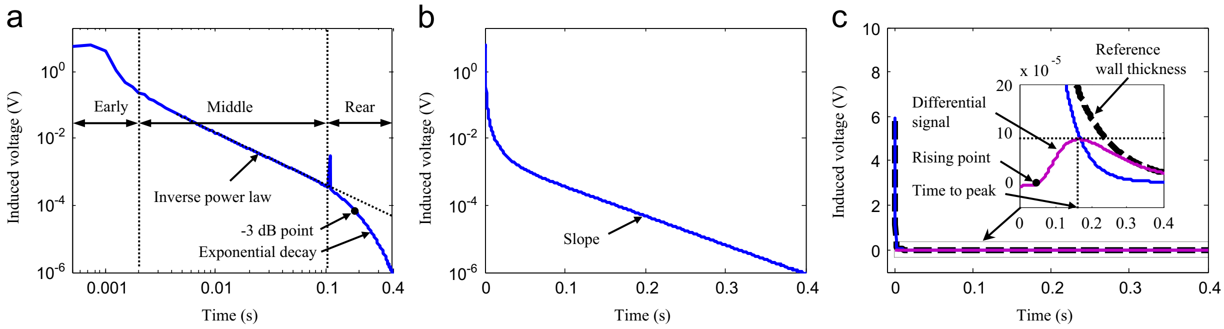

Fig. 1. Typical ferromagnetic PECT signals and features plotted in (a) log–log, (b) semi-log and (c) Cartesian coordinates.

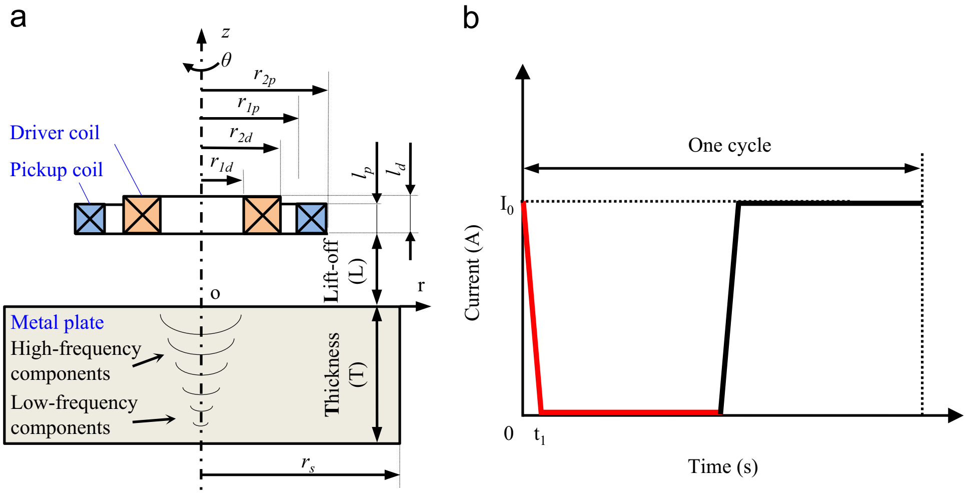

Fig. 2. (a) Schematic and (b) excitation current waveform of PECT.