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Pulse-modulation eddy current inspection of subsurface corrosion in conductive structures

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ABSTRACT

Due to corrosive and hostile environment, in-service conductive structures are prone to subsurface corrosion which has posed a severe threat to structural integrity and safety. Although Pulsed eddy current testing (PEC) has been found advantageous over other Electromagnetic Non-destructive Evaluation (ENDE) techniques particularly in detection and characterisation of subsurface defects in conductive structures, it is subject to technical drawbacks. In light of this, in this paper, Pulse-modulation eddy current technique (PMEC) is proposed in an effort to enhance the inspection sensitivity to subsurface corrosion and quality of corrosion imaging. Closed-form expressions of PMEC responses to subsurface corrosion are formulated via the Extended Truncated Region Eigenfunction Expansion (ETREE) modelling. A series of simulations are subsequently conducted to analyse the characteristics of PMEC signals and inspection sensitivity. Following this, experiments of PMEC for evaluation and imaging of subsurface corrosion are carried out. Through theoretical and experimental investigation, it has been found that PMEC is advantageous over PEC in terms of evaluation sensitivity and quality of corrosion imaging.

1. Introduction

Compared with traditional Eddy Current (EC) techniques including Single- or Multi-frequency Eddy Current [1] and Sweep-frequency Eddy Current [2,3], Pulsed Eddy Current technique (PEC) has been found to be advantageous particularly in evaluation, characterisation and identification of subsurface defects in in-service conductive structures [4–7]. The significant difference between PEC and other EC lies in the waveform of the excitation current which drives the excitation coil for generation of the incident field. In lieu of sinusoidal waveform for EC, PEC utilises the excitation current in a waveform similar to the rectangular waveform, which is presented in Fig. 1(a). As shown in Fig. 1(a), the PEC current signal can be discretised into an infinite train of sinusoidal waveforms. This indicates that the information regarding structural integrity, which could be extracted from EC with a large number of sinusoidal excitations with various frequencies, can be acquired by using PEC with a single excitation process [8].

In consideration of skin effect of electromagnetic field and spectral analysis of the PEC excitation current, it is noticeable that PEC actually implements the inspection from the conductor surface (due to high-frequency harmonics) to infinite depth (due to DC). Whereas, close-up investigation of Fig. 1(a) indicates the technical drawback which undermines PEC. Even though the rising and falling parts of the current signal influence the harmonics in excitation, a large amount of excitation energy is allocated to DC component which is barely useful for generation of eddy currents, whilst the energy allocated to excitation harmonics corresponding to eddy-current penetration depths up to a conductor thickness is considerably lower. Such technical drawback hinders the enhancement of inspection sensitivity and evaluation accuracy of PEC, even though researchers have proposed a number of counter-measures in probes and signal processing, etc. [4,9,10].

The demand regarding mitigation of the technical drawback opens up the pursuit of an appropriate waveform for the excitation current, which allocates sufficient excitation energy to harmonics inducing eddy currents within the conductor effective for evaluation of defects at the depth of interest. In light of this, this paper proposes Pulse-modulation eddy current technique (PMEC) which employs the excitation current in Pulse Modulation Waveform (PMW) normally adopted in millimetre wave testing [11] and radar technologies [12]. From Fig. 1(b), it can be seen that the excitation energy could be allocated to the effective harmonics by adjusting the fundamental frequencies of the carrier and modulation signals, whilst the characteristics similar to PEC in terms of broad-band and low-power-consumption excitation are secured.

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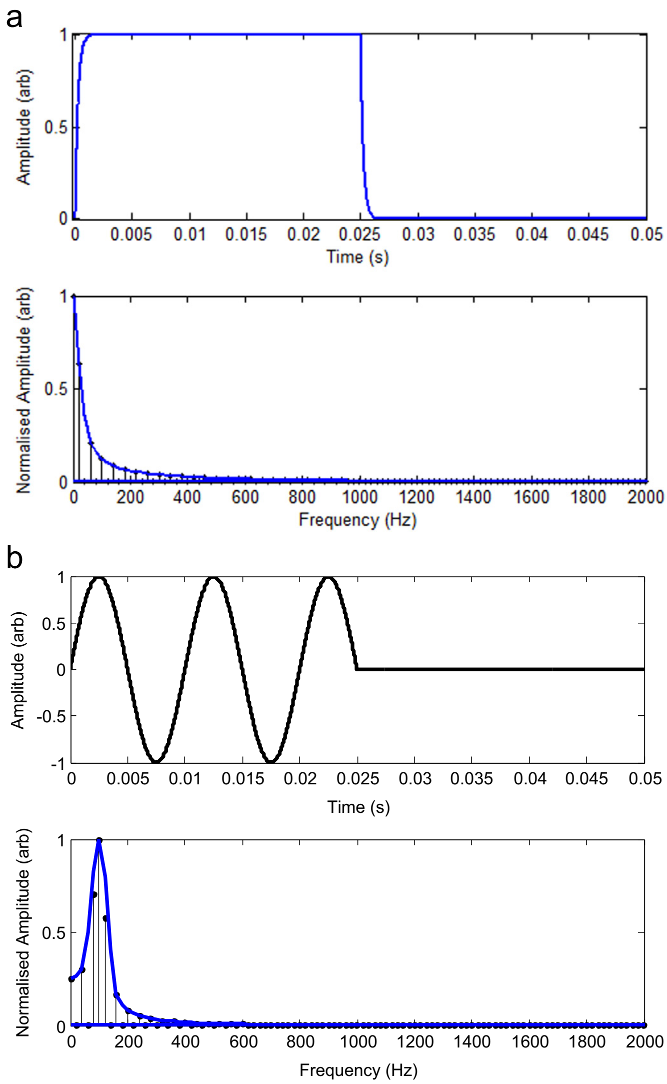

Fig. 1. Temporal signals and spectra of: (a) PEC excitation current with the unit amplitude and fundamental frequency of 20 Hz and (b) the unit-amplitude pulse modulation waveform with frequencies of the carrier and modulation signals at 100 Hz and 20 Hz, respectively.

In this paper, PMEC for detection, evaluation and imaging of subsurface corrosion which has been posing a severe threat to integrity and safety of conductive structures is intensively investigated via theory and experiments. The advantage of PMEC over PEC is identified. The rest of the paper is organised as follows: Section 2 presents theoretical investigation of PMEC based on the Extended Truncated Region Eigenfunction Expansion (ETREE) modelling [13]. The expressions of the PMEC signal and its response to initial subsurface corrosion are formulated. The comparison of inspection sensitivity between PMEC and PEC is conducted via a series of simulations. The experimental investigation regarding PMEC of localised subsurface corrosion and comparison of PMEC with PEC in terms of evaluation sensitivity and imaging quality are elaborated in Section 3.

2. Theoretical investigation

2.1. Formulation of PMEC signals

Since both PMEC and PEC are related to the transient eddy current problem, ETREE modelling previously utilised for PEC modelling could be applicable for PMEC. Suppose that a cylindrical probe is placed over a stratified conductor, which is shown in Fig. 2. The probe consists of: (1) an excitation coil generating the primary/incident field to induce eddy currents in the conductor and (2) a solid-state magnetic field sensor placed at the centre of the excitation coil for picking up transient signals of the net field which is the superposition of the primary field and secondary field induced by eddy currents in the conductor.

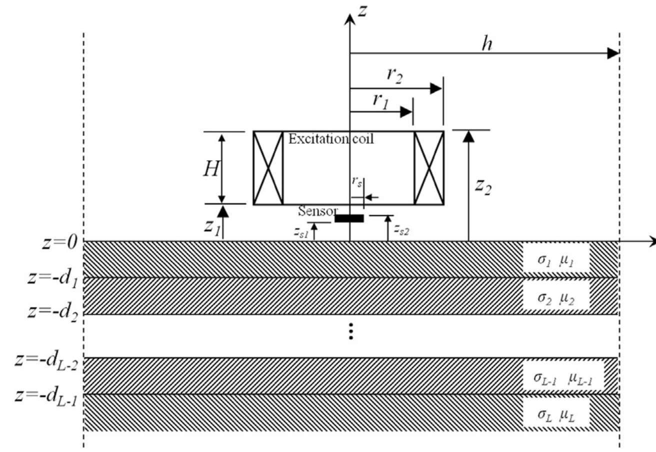

Fig. 2. A cylindrical probe of PMEC above a stratified conductor in the truncated region.

Through ETREE modelling, the closed-form expressions of transient signals $B(t)$ acquired from the magnetic field sensor when the excitation coil is driven by an excitation current in arbitrary waveform can be written as [14,15]

$$\begin{cases} B(t) = B_1(t) + B_2(t) \\ B_1(t) = M\sum_{i=1}^{\infty} N\upsilon_1 \left(e^{-a_i z_1} - e^{-a_i z_2}\right)\left(e^{a_i z_{s2}} - e^{a_i z_{s1}}\right) \quad \text{Primary field} \\ B_2(t) = M\sum_{i=1}^{\infty} N\upsilon_2 \left(e^{-a_i z_2} - e^{-a_i z_1}\right)\left(e^{-a_i z_{s2}} - e^{-a_i z_{s1}}\right) \quad \text{Secondary field} \end{cases}, \tag{1}$$

where,

$$\begin{cases} M = \frac{2\pi\mu_0 N}{r_s(r_2 - r_1)(z_2 - z_1)(z_{s2} - z_{s1})}; \quad N = \frac{J_1(a_i r_s)\chi(a_i r_1, a_i r_2)}{[hJ_0(a_i h)]^2 a_i^5} \\ \upsilon_1 = \frac{1}{\pi}\int_{-\infty}^{+\infty} I(\omega)e^{j\omega t}d\omega; \quad \upsilon_2 = \frac{1}{\pi}\int_{-\infty}^{+\infty} I(\omega)\eta_i(\omega)e^{j\omega t}d\omega \end{cases}. \tag{2}$$

In Eq. (2), ω is the angular frequency of each harmonic within the pulse excitation. μ_0 is the permeability of vacuum. J_n denotes the Bessel function. N is the number of turns of the coil. h stands for the radial distance of truncated solution region. a_i is the positive root of $J_1(a_i h)=0$. $\eta_i(\omega)$ is the conductor reflection coefficient corresponding to each harmonic, which can be calculated by using the equations presented in [14,15]. The coil coefficient $\chi(a_i r_1, a_i r_2)$ can be computed by referring to the identity in [1].

It is noted that the harmonics $I(\omega)$ within the excitation current are readily computed by means of Fourier Transform (FT) of the temporal current signal, and thus the transient field responses are recovered by using Inverse Fourier Transform (IFT) of spectral field signals over entire harmonics. Whereas, further analysis has revealed that the computation of PMEC signals takes time as FT of the excitation current needs to be computed and a number of excitation harmonics should be taken into account.

In consideration of Fourier theorem, the derivation of $I(\omega)$ by using FT of the excitation current could be neglected by using convolution of time-domain signals [16]. Therefore, the expressions of signals regarding primary and secondary fields in Eq. (1) are modified as

$$B_1(t) = I(t)\cdot\psi = I(t)\cdot\left[M\sum_{i=1}^{\infty} N\left(e^{-a_i z_1} - e^{-a_i z_2}\right)\left(e^{a_i z_{s2}} - e^{a_i z_{s1}}\right)\right] \tag{3}$$