NDT&E International 69 (2015) 28–34

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Pulsed eddy current testing of ferromagnetic specimen based on variable pulse width excitation

Jian Li, Xinjun Wu*, Qing Zhang, Pengfei Sun

School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 23 April 2014
Received in revised form
24 August 2014
Accepted 17 September 2014
Available online 28 September 2014

Keywords:
Pulsed eddy current testing
Variable pulse width excitation
Quantitative detection
Ferromagnetic specimen

ABSTRACT

Pulsed eddy current testing (PECT) is a rapidly developing technology which has wide potential applications. For the PECT system which uses detection coils, a no-reference-needed and more efficient method, for quantifying the wall thickness of the ferromagnetic specimen, should be found. In this paper, a kind of variable pulse width excitation is proposed. Based on the excitation, the slope that the relative increment of magnetic flux linear decays with the increase of pulse width in the semi-logarithmic domain is found to be an effective and no-reference-needed feature. First, the analytical expression for the relative increment of magnetic flux is presented, and the validity of the feature is verified by experiments. Then the potential factors affecting the feature are investigated in detail. Results show that when the electromagnetic properties of the specimen are invariant, the feature is independent of pulse width parameters, analysis interval and coatings thickness. At last, a quantitative method is demonstrated. More time could be saved for the narrow pulse comparing it with the existing excitations, and the feature could widely meet engineering applications.

1. Introduction

A ferromagnetic specimen is commonly used for the pressure equipment. The reliability and safety of the equipment suffer from threats of corrosion. Periodical nondestructive testing is essential to avoid unnecessary loss. However, for the specimen, there is usually coating with thermal insulation to reduce energy loss and covering with cladding to protect the thermal insulation. It is hard to quantify the specimen wall thickness in the multilayer structure with conventional detection methods. Pulsed eddy current testing (PECT), which is a rapidly developing nondestructive testing technology, becomes a powerful candidate for those applications. However, for the PECT system which uses detection coils, the existing signal interpretations are reference-needed and they should keep the coatings thickness invariable in testing [1,2], while these requirements are difficult to meet because of the inevitable deformation and installation error. Therefore, a no-reference-needed method, for quantifying the wall thickness of the ferromagnetic specimen, should be found.

Through loading of the variable duty cycle excitation, a no-reference-needed method has been found for defect location detection in a multi-layer non-ferromagnetic specimen [3,4], while for the wall thickness quantification of the ferromagnetic specimen, the existing variable duty cycle excitation might be unadaptable. On one hand, the eddy current phenomenon is a diffusion process [4], and the diffusion time is positively related with the electrical conductivity and the magnetic permeability of the specimen [5]. For the ferromagnetic specimen, diffusion time is much longer due to the bigger magnetic permeability and similar electrical conductivity. On the other hand, as time goes on, the diffusion process becomes more and more related to specimen thickness; information about specimen thickness is mainly included in the rear part of the signal [6,7]. Therefore, wall thickness quantification of a ferromagnetic specimen needs longer space time between the neighboring pulses for signal acquisition. However, the analysis interval of the thickness-related signal is almost kept the same when the duty cycle has changed [8]. For the existing variable duty cycle excitation, whose repetition frequency is constant, the maximal duty cycle determines the maximal detection depth [3,4]. If the space time of the maximal duty cycle is appropriate to a certain thickness, for the smaller duty cycle, more time will be wasted because of the longer space time. In order to improve the detection efficiency, a kind of variable pulse width excitation is proposed in this paper.

Different from the existing excitation, the repetition frequency of the excitation proposed in this paper is variable. As shown in Fig. 1, the excitation is composed of a sequence of rectangular

* Correspondence to: Room B503, East of Advanced Manufacture Building, 1037 Luoyu Road, Wuhan 430074, Hubei Province, China.
Tel.: +86 27 8755 9332; fax: +86 27 8755 9332.
E-mail addresses: smartlijian@mail.hust.edu.cn (J. Li), xinjunwu@mail.hust.edu.cn (X. Wu), hustzhangqing@mail.hust.edu.cn (Q. Zhang), hustpfs@mail.hust.edu.cn (P. Sun).

http://dx.doi.org/10.1016/j.ndteint.2014.09.004
0963-8695/

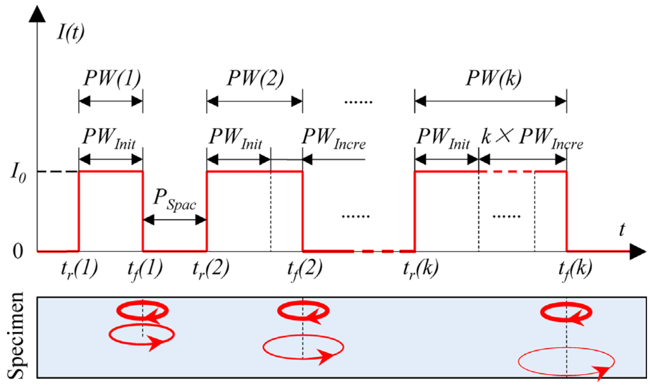

Fig. 1. Variable pulse width excitation and the induced eddy currents.

pulses, whose pulse widths are gradually increased with a constant pulse width increment, and the space time, between neighboring pulses, is also constant. The counteraction, which occurs between the eddy currents induced at the rising and falling edges of a pulse, is not only related to the pulse width, but also to the specimen wall thickness, because the diffusion process is nonlinear [9,10] and related to the specimen wall thickness [5]. The degree of counteraction can be described by the magnetic flux released from the specimen. In consideration that the existing no-reference-needed method is based on the differential process between the different duty cycles [4], and the magnetic flux of the detection coil is sensitive to the coatings thickness, the relative increment of magnetic flux between neighboring pulses is proposed for extracting the no-reference-needed feature.

The rest of this paper is organized as follows. In Section 2, an analytical model for the variable pulse width excitation is presented. Based on the model, a no-reference-needed feature is extracted. In Section 3, an experimental setup is constructed to verify the validity of the feature. In Section 4, the potential factors affecting the feature are investigated in detail. In Section 5, a quantitative method is demonstrated. In Section 6, a brief conclusion is given.

2. Feature extraction based on the analytical model analysis

2.1. Analytical model for the variable pulse width excitation

With regard to the variable pulse width excitation shown in Fig. 1, the response of PECT can be calculated with the analytical model [2]. In the analytical model, the specimen coating with thermal insulation and cladding is approximated to a four-layered structure as shown in Fig. 2a. For convenience of solution, the entire space is divided into five regions along with the z direction. From bottom to top, the magnetic permeability and the electrical conductivity of each layer are denoted by μ_t and σ_t (t=1, 2, 3, 4, 5). After applying the truncated region eigenfunction expansion (TREE) method and imposing a magnetic insulation boundary at $r=h$ [11], the frequency-domain response $\Delta U(\omega)$ of harmonic components is deduced to Eq. (1). It is only from the layered structure and can be used to evaluate the specimen thickness.

$$\Delta U(\omega)=\frac{j2\pi\omega n_d n_p \mu_0 I(\omega)}{(r_{2d}-r_{1d})(l_{2d}-l_{1d})(r_{2p}-r_{1p})(l_{2p}-l_{1p})} \times \sum_{i=1}^{\infty}\chi(\alpha_i r_{1d},\alpha_i r_{2d})\chi(\alpha_i r_{1p},\alpha_i r_{2p})\frac{(e^{-\alpha_i l_{2d}}-e^{-\alpha_i l_{1d}})(e^{-\alpha_i l_{2p}}-e^{-\alpha_i l_{1p}})}{[(a_i h)J_0(a_i h)]^2\alpha_i^5} \Gamma(a_i,\omega) \quad (1)$$

where j is the imaginary unit, ω is the angular frequency of harmonic component, n is the number of the coil turns, μ_0 is the permeability of free space, $I(\omega)$ is the amplitude of the harmonic component and $I(\omega)=\int_{-\infty}^{+\infty}I(t)e^{-j\omega t}dt$, $\chi(x_1,x_2)=\int_{x_1}^{x_2}xJ_1(x)dx$, $J_0(x)$ and $J_1(x)$ denote the zero-order and first-order Bessel function of the first kind, respectively, α_i is the i-th positive root of the Bessel function $J_1(\alpha_i h)$, and $\Gamma(\alpha_i,\omega)$ is the reflection coefficient of the layered structure, which can be derived by Cheng's matrix method [12]. The denotations of the other parameters are shown in Fig. 2a. The subscripts d and p are on behalf of the driver coil and the pickup coil, respectively.

The time–domain response $\Delta U(t)$ can be deduced by transforming $\Delta U(\omega)$ with inverse Fourier transform shown in Eq. (2).

$$\Delta U(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\Delta U(\omega)e^{j\omega t}d\omega \quad (2)$$

Thus the analytical model is applicable to calculate the response of arbitrary excitation waveform. However, the length of excitation Len_{Exc} and the number of pulses N_p should be finite because the length of register is limited. The excitation with variable pulse width is expressed as follows:

$$I(t)=\begin{cases} I_0, & t\in[t_r(k),\ t_r(k)+PW(k)], \quad k=1,2,\cdots,N_p \\ 0, & \text{others}\end{cases} \quad (3)$$

where I_0 is the amplitude of pulse sequence, k is the sequence number of pulse, $t_r(k)$ is the time corresponding to the rising edge of k-th pulse, $PW(k)=PW_{Init}+(k-1)PW_{Incre}$ is the pulse width of the k-th pulse, PW_{Init} is the width of the initial pulse, and PW_{Incre} is the increment of pulse width.

The PECT signal in the low-level segment of excitation at each pulse is expressed as follows:

$$\Delta U_{PW(i)}(t)=\Delta U(t),\ t\in[t_f(k),t_f(k)+P_{Spac}], \quad k=1,2,\cdots,N_p \quad (4)$$

where $t_f(k)$ is the time corresponding to the falling edge of k-th pulse and P_{Spac} is the space time between neighboring pulses. The relative increment of magnetic flux is expressed as follows:

$$MF_{Re\ laIncre}(k)=\frac{\int_{t_f(k+1)+t_1}^{t_f(k+1)+t_2}\Delta U_{PW(k+1)}(t)dt-\int_{t_f(k)+t_1}^{t_f(k)+t_2}\Delta U_{PW(k)}(t)dt}{\int_{t_f(k)+t_1}^{t_f(k)+t_2}\Delta U_{PW(k)}(t)dt}, \quad k=1,2,\cdots,(N_p-1) \quad (5)$$

where t_1, t_2 are the starting time and ending time of analysis interval, respectively, and t_1, $t_2\in[0, P_{Spac}]$, $t_1<t_2$. It is related to both the pulse width and the specimen wall thickness.

2.2. Feature extraction

In the analytical calculation, the parameters are set as follows. The number of turns, inner diameter, outer diameter and height of the driver coil are 800, 32 mm, 80 mm and 34 mm. The corresponding parameters of the pickup coil are 1200, 144 mm, 152 mm and 6 mm. The thickness, electrical conductivity and relative permeability are set to 15 mm, 1.6 MS/m and 600, respectively. For the thermal insulation, which is usually made of electrical insulating material, the corresponding parameters are set to 20 mm, 0 MS/m and 1. For the cladding, the corresponding parameters are set to 0.5 mm, 2.0 MS/m and 300, which are the common specification widely used in the industry and the electromagnetic properties of the galvanized steel sheet. When the excitation parameters are set as I_0=4 A, PW_{Init}=25 ms, PW_{Incre}=25 ms, P_{Spac}=1000 ms, N_p=6 and Len_{Exc}=10 s, the PECT signals at different pulse widths can be obtained and three of them are drawn in the double-logarithmic domain as shown in Fig. 2b. The signal amplitudes increase with pulse width. It indicates that the counteraction of the opposite direction eddy currents becomes weaker for the longer pulse. The