NDT&E International 69 (2015) 35–39

Contents lists available at ScienceDirect

NDT&E International

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

An improved ferromagnetic material pulsed eddy current testing signal processing method based on numerical cumulative integration

Chen Huang [a], Xinjun Wu [b,*]

[a] Science and Technology on Electromagnetic Compatibility Laboratory,Wuhan 430064, PR China
[b] School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form
16 September 2014
Accepted 18 September 2014
Available online 28 September 2014

Keywords:
Pulsed eddy current testing
Ferromagnetic material
Signal processing
Cumulative integration

ABSTRACT

A pulsed eddy current (PEC) testing signal processing method for ferromagnetic material is presented. Without any filtering process that may produce signal distortion, the numerical cumulative integration of the noisy PEC signal is calculated and subsequently fitted to the theoretical model. The model parameter estimation is later applied to quantify the specimen thickness and reconstruct a denoised PEC signal. A comparison is made between the presented method and the former direct-fitting method. The results demonstrate that the presented method improves the testing performance in terms of the detectable thickness range, the probe lift-off distance, and the measuring time.

1. Introduction

Pulsed eddy current (PEC) testing technology is becoming widely used in the field of non-contacting large-area corrosion detection for ferromagnetic vessels and pipes. Much effort has been undertaken to obtain a theoretical model for a specific testing condition. A field-theory-based analytical solution for a PEC signal on a conducting half-space was presented by John Bowler and Marcus Johnson [1]. Subsequently, V. O. De Haan expanded the research to the finite-thickness specimen case and calculated the theoretical PEC responses for the ferromagnetic plate [2]. Lefebvre et al. presented a circuit-based transformer model [3] for a non-ferromagnetic thin-plate PEC signal [4]. Recently, progress has been made in defect characterization [5,6] and signal simulation [7] via PEC technology. However, all of these studies have placed an emphasis on theories or experiments and have seldom discussed the model-fitting method, the results of which are sensitive to noise impacts and other fitting conditions.

According to the eddy-current diffusion theory [8], the PEC signal from a ferromagnetic material decays more slowly than that of a non-ferromagnetic material. The latter part of the signal that carries important information of the specimen thickness is very weak and is usually severely contaminated by environmental noise. This situation introduces difficulty in signal parameterization when the data are directly fitted to the theoretical model. Our previous research presented a ferromagnetic material pulsed eddy current signal model based on multiple-coil coupling theory [9]. The original PEC signal is first pre-processed by a double-logarithmic filtering process [10] and then fitted to the model. Although the experimental results verify the validity of the model, the model-fitting performance should be improved.

This paper presents a cumulative integration-based method for PEC signal processing. This method does not require a filtering process because it is insensitive to environmental noise. The integration process effectively reduces the noise impacts without signal distortion. The testing efficiency and the accuracy of the parameter estimation are both increased.

2. Methods

Previous research [9] indicates that the theoretical PEC signal may be modeled by:

$$v_{theoretical}(t) = \sum_{k=1}^{n} B_k e^{-C_k t}, \quad (1)$$

where $v_{theoretical}(t)$ is the theoretical time-domain PEC signal and n is the effective order of the model. B_k and C_k are the parameters to be determined. The value of C_1 monotonically varies as the specimen thickness changes and C_1 is selected as the key parameter to determine the thickness.

* Corresponding author. Tel./fax: +86 27 87559332.
E-mail addresses: rambo_ch@sina.com (C. Huang), xinjunwu@mail.hust.edu.cn (X. Wu).

http://dx.doi.org/10.1016/j.ndteint.2014.09.006
0963-8695/

Noise exists in a measured PEC signal. Thus, the measured PEC signal can be expressed as

$$v_{measured}(t) = v_{theoretical}(t) + v_{noise}(t), \tag{2}$$

where $v_{noise}(t)$ is the time-domain noise signal.

If the integration in the time domain is applied to both sides of Eq. (2), we obtain the following:

$$\Phi(T1,\ T2) = \int_{T1}^{T2} v_{theoretical}(t)dt + \int_{T1}^{T2} v_{noise}(t)dt. \tag{3}$$

The left side of Eq. (3) is the integration of $v_{measured}(t)$ as a function of $T1$ and $T2$. This part corresponds to the magnetic flux passing through the detection coil during the time interval $[T1,\ T2]$. Taking $T1$ as a constant and $T2$ as a variable, $\Phi(T1,\ T2)$ is simplified to $\Phi(T2)$. For a measured PEC signal with a recording time of Tr, $T2$ varies over $[T1,\ T1+Tr]$ and $T1$ is approximately zero. The order of Tr may be estimated by the diffusion theory [8] so that Tr is determined prior to the sampling frequency.

Let us consider the right side of Eq. (3). For a noisy PEC signal obtained by the experimental system with the DC offset removed, the time-domain mean-value of the noise component is approximately zero if the recording time is long enough, i.e., if the signal meets the condition $T2 \gg T1$, we have:

$$\frac{1}{T2-T1}\int_{T1}^{T2} v_{noise}(t)dt \approx E(v_{noise}(t)) = 0, \tag{4}$$

where $E(v_{noise}(t))$ is the mathematical expectation of $v_{noise}(t)$. Eq. (4) indicates that $\int_{T1}^{T2} v_{noise}(t)dt$ may be ignored for the rear part of the signal.

In the initial part of the PEC signal, the condition $T2 \gg T1$ is untenable. Fortunately, the magnitude of $v_{theory}(t)$ is very large, and the signal-to-noise ratio (SNR) is high during this time interval. Therefore

$$\int_{T1}^{T2} v_{theoretical}(t)dt \gg \int_{T1}^{T2} v_{noise}(t)dt \tag{5}$$

and $\int_{T1}^{T2} v_{noise}(t)dt$ can still be ignored.

According to Eqs. (4) and (5), the term $\int_{T1}^{T2} v_{noise}(t)dt$ in Eq. (3) can be omitted regardless of $T2$. Therefore, we obtain

$$\Phi(T2) \approx \int_{T1}^{T2} v_{theoretical}(t)dt. \tag{6}$$

Substituting Eq. (1) into Eq. (6) yields the following:

$$\Phi(T2) = Z - \sum_{k=1}^{n} \frac{B_k}{C_k} e^{-C_k T2}, \tag{7}$$

where Z is a constant that is determined by the constant $T1$ and the second term on the right side is a function of $T2$. The left side of Eq. (7) is the time-domain data that is to be fitted, and the right side is the analytical expression of the model. The second term on the right side of Eq. (7) actually has the same form as Eq. (1). This similarity indicates that the curve-fitting model and the algorithm in reference [9] may be applied to determine the parameters with only minor modifications.

When the fitting process is completed, the fitted curve $\Phi(T2)$ can be synthesized by the estimated parameters Z, B_k, and C_k. This is a "pure" integration curve without any noise. Next, a differential process is applied to this curve to achieve an estimated PEC signal. This process is expressed as:

$$v_{estimated}(T2) = d\left(\hat{\Phi}(T2)\right)/d(T2). \tag{8}$$

The function is independent of the variable name. Replacing $T2$ by t yields

$$v_{estimated}(t) = d\left(\hat{\Phi}(t)\right)/dt = d\left(\sum_{k=1}^{n} \frac{\hat{B}_k}{\hat{C}_k} e^{-\hat{C}_k t}\right)/dt. \tag{9}$$

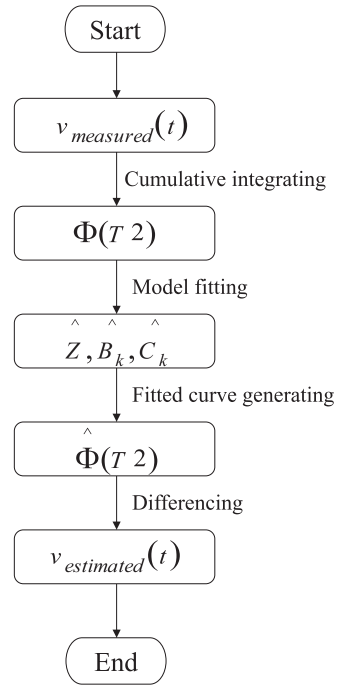

Fig. 1. The process of the method presented.

An experimental PEC system digitizes $v_{measured}(t)$ as a discrete time-domain series, such that $\Phi(T2)$ is calculated by numerical cumulative integration, in which the trapezoidal rule is applied. An over-sampling technique may be applied to obtain enough samples to exhibit the statistical property of the noise for a fixed Tr. The differential process in Eq. (8) is replaced by numerical differencing process. Fig. 1 illustrates the entire process of the method presented.

The method mainly includes three steps: cumulative integrating, fitting and differencing. Hereafter, the process is referred to as the CIFD method.

Eqs. (8) and (9) are a standard process to obtain the estimated PEC signal. In fact, the estimated PEC signal may be obtained directly by

$$v_{estimated}(t) = \sum_{k=1}^{n} \hat{B}_k e^{-\hat{C}_k t}. \tag{10}$$

This step is more convenient in practical manipulation, and it can avoid the problem of data-index mismatching caused by the digital differencing process.

3. Experiment

The purpose of the current experiment is to verify whether the presented CIFD method is capable of processing the signals with a poor signal-to-noise ratio (SNR). As a comparison, the direct-fitting method and the CIFD method are both applied to analyze a same group of measured PEC signals. The parameter estimation results for both methods will be recorded, with the value of parameter C_1 being the eigenvalue [9] for the thickness quantitative analysis.

3.1. Experiment setup

The PEC signals are acquired from a Q235 steel step wedge plate using the experimental system developed by the authors [10]. The nominal thicknesses of the zones to be tested are 10 mm, 15 mm, 20 mm, 25 mm and 30 mm. The excitation current