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A model-based ultrasonic quantitative evaluation method for bonding quality of multi-layered material

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ABSTRACT

Reflection coefficients play an important role in the quantitative evaluation of the bonding quality of the interfaces of the multi-layered composite material. This paper proposes a reflection coefficient-based echo signal model and a new Gaussian model based blind deconvolution method for extracting reflection coefficients of bonding interface. The traditional deconvolution problem can be converted into a parameters estimation process in this model. Moreover, in order to avoid the potential computational burden caused by multiple parameters estimation and the much dependence on the initial parameter values during the estimation process, empirical mode decomposition (EMD) method and an improved Genetic Algorithm are used for parameters estimation. Simulation experiment verified the reliability of this method at different signal-to-noise ratio and with different initial parameter values, and then, reflection coefficients reconstruction of a metal multi-layered composite material specimen is performed through measurement experiment and the result is satisfying. Both the simulation and measurement experiments proved the feasibility and validity of this method.

1. Introduction

Bonding technology has been widely applied in modern industrial field. The bonding quality of materials directly determines the mechanical performance and service effect of the components made of such bonding composite material. The technology of quantitative evaluation for bonding quality has been an extremely important research field recently [1,2]. The non-destructive ultrasonic testing method is a convenient and reliable detection method for evaluating the bonding quality of multi-layered material [3,4]. Among numerous non-destructive ultrasonic testing methods, ultrasonic pulse echo technology is commonly applied to evaluate the bonding quality. Good bond will receive weak echo signal reflected from interface, whereas a debonding interface produces strong echo signals, and the echo strength increases with debonding degree. So we can see ultrasonic echo signal contains information of interface bonding quality. How to extract the information is a critical step toward the quantitative evaluation of bonding quality. However, with respect to practical ultrasonic testing, the surface of the multi-layered material sometimes is not smooth, so the uniformity of the insonifyed wave energy cannot be assured, thus the bonding quality evaluated only with respect to echo signal strength of interface is not reliable enough. Under this circumstance, we should use signal processing technology, such as deconvolution, to reconstruct reflection coefficients of interface, and the obtained reflection coefficients will be used in quantitatively evaluating bonding quality of interface.

Traditional deconvolution methods, such as Wiener filtering, Jansson iteration and high-order spectrum deconvolution, are very sensitive to the accuracy of the convolution kernel [5,6]. Therefore, a function of the convolution kernel which can accurately reflect system performance is needed, or else false results would be obtained. Under normal cir-

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cumstances, a function of convolution kernel can be derived through experimental methods. However, with respect to ultrasonic practical testing, it is relatively difficult to get an accurate convolution kernel through experimental methods in which ultrasonic signal has distortion in waveform during the propagation due to the frequency dependent attenuation. So this lack of universality of traditional deconvolution methods makes them rather confined in application. So we need to find a good method to estimate the reflection coefficients of the interface. Compared with traditional deconvolution methods, blind deconvolution does not require a well-prepared convolution kernel [7,8]. In this paper, a new Gaussian model based blind deconvolution method using EMD for pre-processing is proposed to get reflection coefficients of bonding interfaces for the purpose of the quantitative evaluation of the bonding quality of the interfaces. EMD is used to decompose the echo signal by different frequency bands, a process much like sub-band filtering. Then, the Gaussian model based blind deconvolution is applied to those sub-band signals. Moreover, in order to avoid the much dependence on the initial parameter values during the estimation process, an improved Genetic Algorithm is used for parameters estimation in the deconvolution process. By this means, the reflection coefficients of bonding interface can be obtained.

2. Reflection coefficient-based echo signal model

Fig. 1 shows the ultrasonic signals reflected from interfaces of the multi-layered composite material. Ultrasonic transducer transmits ultrasonic signal $p(t)$, when the incident signal $p(t)$ encounters an interface, one portion of it is reflected back to the transducer and the other portion passes through the interface, and then continues to propagate. The amplitude of echo reflected from the debonding interface is higher than that of echoes from the no debonding interface, which implies that the reflection coefficients of the debonding interface are bigger than that of no debonding interface. So we can evaluate the bonding quality of multi-layered material using the reflection coefficients. $f_1, f_2, \ldots, f_M$ represent the reflection coefficients of the corresponding interface. Suppose the signal that reaches the first interface is $p(t-t_1)$, so echo signal reflected from this interface can be

$$s_1 = f_1 p(t - t_1 - t_1) = f_1 p(t - 2t_1) \quad (1)$$

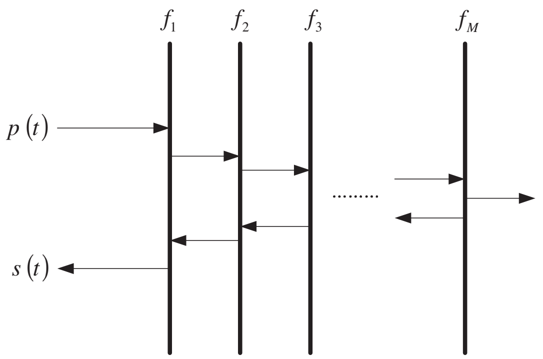

Fig. 1. Schematic of ultrasonic reflection at interfaces.

The signal that passes through the first interface is

$$p(t - t_1) - f_1 p(t - t_1) = (1 - f_1) p(t - t_1) \quad (2)$$

Then, echo signal from ith interface is

$$s_i = f_i \prod_{k=1}^{i-1} (1 - f_k) p(t - 2t_i) \quad (3)$$

wherein t_i represents the arrival time of echo signal reflected from ith interface. Therefore, the total echo signals received can be

$$s(t) = \sum_{i=1}^{M} f_i \left(\prod_{k=1}^{i-1} (1 - f_k) p(t - 2t_i) \right) \quad (4)$$

From the mathematical model as shown in Eq. (4), we can see that the received signal $s(t)$ can be represented as a convolution of the reflection coefficient f_i and the transmitted signal $p(t)$, and the value of f_i is larger in the debonding interface than that in the no debonding interface. In order to get the value of f_i, the deconvolution technique is needed, which can give a series of impulses of which position and amplitude correspond to the location of the interface and the reflection coefficient respectively. From this, the bonding quality of all interfaces can be evaluated. We can easily obtain the reflection coefficients in the frequency domain using the Fourier transform. However, the transmitted signal $p(t)$ is a band-limited signal, and a little jamming will bring a big error to the results of deconvolution. So we need to find a good method to estimate the reflection coefficients of the interface.

3. Improved Gaussian model based blind deconvolution

The magnitude spectrum of the transducer transmitted signal $p(t)$ has band-pass characteristics. So the time domain representation of the transmitted signal can be modeled by a number of band-pass signals [9],

$$p(t) = \sum_{n=1}^{N} c_n \exp\left[-\alpha_n t^2\right] \cos(2\pi f_{cn}(t + \varphi_n)) + n(t) \quad (5)$$

wherein f_{cn} is the central frequency, α_n is the bandwidth factor, c_n is the amplitude, and φ_n is the phase, $n(t)$ represents the noise comes from measurement and can be characterized as the additive Gaussian white noise. N is the model order, i.e., the number of Gaussian echoes. Substituting Eq. (5) into Eq. (4), we have the following formula.

$$s(t) = \sum_{i=1}^{M} f_i \left(\prod_{k=1}^{i-1} (1 - f_k) \sum_{n-1}^{N} c_n \exp[-\alpha_n (t - t_i)^2] \cos(2\pi f_{cn}(t + \varphi_n - t_i)) \right) + n(t) \quad (6)$$

In order to decrease the model order N during the estimation process, a EMD transform is used to decompose the received reflected signal by different frequency bands, a process much like sub-band filtering. EMD is a new signal decomposition method, which was introduced by Huang et al. to analyze data from non-stationary nonlinear processes. The major advantage of EMD is that the basis function is derived from the signal itself. Hence, the analysis is adaptive in contrast to the wavelet transform or short-time