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An experimental method to measure the layer thickness and wave velocity of copper–steel composite board without interface echo

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ABSTRACT

Thickness of each medium layer and velocity of ultrasonic wave propagation in each medium layer of the two-layer composite medium were measured simultaneously based on the method to collect phase information from continuous echo signals on front surface and undersurface. Such measurement was implemented under no interface echo and fixed total thickness of the testpiece. The method can be applied to any two kinds of two-layer composite medium. The paper only used a 35 mm thick copper–steel composite board as an experimental example. Calculated results demonstrated that measuring errors of both thickness and velocity of ultrasonic wave propagation are smaller than 0.2%, indicating the effectiveness of the proposed measurement method.

1. Introduction

In ultrasonic nondestructive testing (NDT), many different methods have been used to define characteristics of multi-layer medium [1–5]. Most of them are based on different amplitudes of different interface echo signals in layered medium, which have two prominent problems that have attracted wide attentions: (1) upon impedance mismatching between two media, amplitude of interface reflection echo will decrease to nearly same with noise; (2) given small layer thickness, echoes of the weak interface and strong interface will overlap with each other, especially the reflective echo of the testpiece surface and that of far side interface like undersurface. The third problem will occur when the diffuse interface couldn't generate interface reflective echo. In signal analysis, if even a faint interface echo is difficult to be generated, reliability of different algorithms will be reduced [6]. Moreover, if there's no interface echo during the detection, these technologies will become useless.

In this paper, a new detection method is proposed to solve problems of two-layer medium without reflective echo interfaces. It makes full use of the phase delay between generating front surface echo and undersurface echo by the Wears incident pulse. Such phase delay is composed of the wave between two media and the wave passing through the diffuse interface. Spatial length of the diffuse interface ranges from submicrons to micron. Since layer thickness has to be controlled at millimeter, it was suggested to viewing the diffuse interface as a pseudo-interface, a two-layer separation zone in the average sense. A simple search is made in three parameter spaces. In other words, thickness of one layer and velocity of ultrasonic wave between two layers are determined by the least squares of phase delay. In the paper, we only use the copper–steel composite board to do the experiment to show the correctness of the method. In fact, for any of two-layer composite media, such as nickel–chromium, nickel–copper, white iron-gray iron, etc, thickness and ultrasonic propagation velocity can also be measured in each layer of the medium in this way. The experiment on the composite board with 10 mm thick copper layer showed that this method is quite reliable to typical noise levels and typical test error during the arrival of rear surface signal. Although is only used in three-dimensional parameter spaces, we hope there will be more advanced search methods to handling more complicated multi-layer composite medium.

2. Method

Suppose the total thickness of the testpiece is fixed and the goal is to estimate thickness of each layer. This can be solved by the approximation problem of a two-layer model. The two-layer medium is composed of material *A* and *B*, which won't produce any measuring signals on the interfaces in water immersion ultrasonic pulse echo test system. Its structure is shown in Fig. 1.

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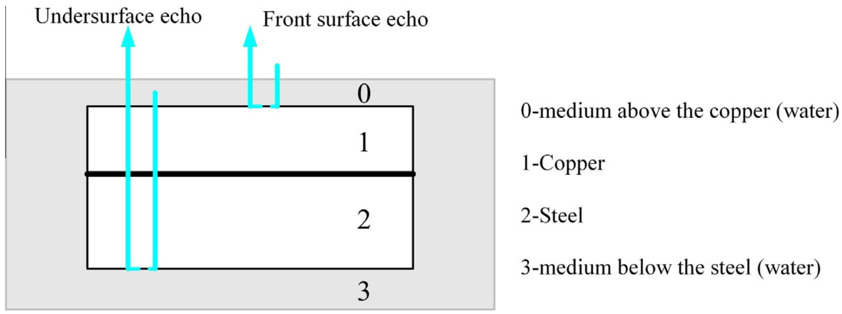

Fig. 1. Multiple reflections in the testpiece.

Due to sound impedance mismatching, the wideband signal passing through the two-layer medium generates front surface echo on the medium *A*–water interface and undersurface echo on the medium *B*–water interface. Since dispersion effect won't exist in these two materials, it isn't discussed in this paper.

Suppose it is a plane wave propagation, then effective reflectance of waves of every frequency in the wideband signal in the two-layer medium could be calculated. The following text refers to Refs. [7,8]. As shown in Fig. 1, effective reflectance within the structural frequency range is calculated through two steps. Firstly, according to the effective reflectance of the second and third layer, it can be calculated from Eq. (1) that:

$$R_{12\text{net}} = R_{12} + \frac{T_{12}R_{23}T_{21}e^{[-2i(k_2d_2)]}}{1 - R_{23}R_{21}e^{[-2i(k_2d_2)]}} \tag{1}$$

where $R_{12\text{net}}$ is the effective reflectance of 1–2 interface covering medium 2 and 3. Secondly, the effective reflectance of the whole testpiece is calculated from Eq. (2) (deduction details are presented in Appendix A).

$$R_{\text{net}} = R_{01} + \frac{T_{01}R_{12\text{net}}T_{10}e^{[-2i(k_1d_1)]}}{1 - R_{12\text{net}}R_{10}e^{[-2i(k_1d_1)]}} \tag{2}$$

where R_{ij} and T_{ij} are the reflectance and transmission coefficient between medium i and j; d_1 and d_2 are thicknesses of two layers; k_1 and k_2 are wave number in two layers in corresponding to *P*-wave; the factor 2 represents two propagation modes of waves.

When limited to time-domain reversal and experimental study, the expression characterizes the multiple reflection echo. Since all interests are paid to the second undersurface echo which is appeared for the first time, expression of the effective reflectance in Fig. 1 is expanded as an interceptive sequence:

$$\begin{aligned} R_{\text{net}} &= R_{01} + T_{01}T_{10}(T_{12}R_{23}T_{21})e^{[-2i(k_1d_1+k_2d_2)]} \\ &\quad + T_{01}T_{10}(T_{12}R_{23}T_{21})^2R_{10}e^{[-4i(k_1d_1+k_2d_2)]} \end{aligned} \tag{3}$$

This effective reflectance is the second undersurface echo appeared for the first time after the front surface echo when there's no interface echo.

Phase delay between the front surface echo and the first undersurface echo is the last term of the interceptive sequence, which is characterized by the factor $e^{-2i(k_1d_1+k_2d_2)}$. This phase factor has three unknown variables: d_1 is thickness of one layer, while v_1 and v_2 are velocity of longitudinal waves in two layers, respectively. This technique is to estimate these three unknown variables through the least squares search in the parameter space. Suppose numerical ranges of these three unknown variables are known. Particularly,

(1) Suppose Y_1 and Y_2 represent the time-domain pulse vectors of the first and second undersurface echoes; y_1 and y_2 are their corresponding discrete Fourier Transform vectors, which contain complex number and have same length with the time-domain pulse signal.
(2) Suppose f represents the vector in corresponding with frequency in the time-domain signal.
(3) Suppose d is the thickness of the whole testpiece, while d_1 and d_2 are thicknesses of the first and second layers, which are unknown variables that have to be calculated, $d_1 + d_2 = d, d_1 \in R^+, d_2 \in R^+$.
(4) Suppose v_1 and v_2 are velocity of ultrasonic wave propagation in two layers of medium; k_1 and k_2 are wave numbers in two layers of medium. All of them are unknown variables, $v_1 \in R^+$, $v_2 \in R^+$.

A series of new vectors (y_{11} and y_{22}) can be gained from normalization of y_1 and y_2, respectively.

$$y_{11}(j) = \frac{y_1(j)}{|y_1(j)|} \quad \text{for} \quad j = 1, 2, \ldots, N \tag{4}$$

When N is used to represent lengths of y_1 and y_2:

$$y_{22}(j) = \frac{y_2(j)}{|y_2(j)|} \quad \text{for} \quad j = 1, 2, \ldots, N \tag{5}$$

Another vector $e^{i\phi}$ is gained by dividing y_{22} by y_{11}.

$$e^{i\phi}(j) = \frac{y_{22}(j)}{y_{11}(j)} \quad \text{for} \quad j = 1, 2, \ldots, N \tag{6}$$

Vector $e^{i\phi}$ shall be equal to $e^{-2i(k_1d_1+k_2d_2)}$ at all frequencies of the bandwidth signal except for the 180° phase change. Such phase change is unrelated with phase change caused by the wave passing through the two-layer medium. Since the wave is reflected by the low-impedance medium, the 180° phase change produced on the undersurface of the Fourier domain is eliminated from analog signal and experiment signal. Since amplitude and phase of the experiment signal contain noises, the measured phase change ϕ is inconsistent with the phase factor ($k_1d_1 + k_2d_2$). Meanwhile, when n is an integer, there will be $2n\pi$ difference between the measured phase change ϕ and actual phase change ϕ_{expt}. Obviously, if ϕ is the measuring phase, it has a $2n\pi$ difference with the actual phase change in the experiment ($\phi_{\text{expt}} = k_1d_1 + k_2d_2$). In other words, when n is an integer, $\phi = \phi_{\text{expt}} + 2n\pi$. Such ambiguity is eliminated by $e^{i\phi}$: $e^{i\phi} = e^{i(\phi+2n\pi)}$. At the same time, people hopes to express $\cos(\phi)$ and $\sin(\phi)$ indirectly by $e^{i\phi}$, which are used as the objective function. This provides a good condition for optimization of the function.

The objective function (G) of least squares error is defined by three parameters, d_1 (or d_2), v_1 and v_2: