Ultrasonics 53 (2013) 1377–1383

Contents lists available at SciVerse ScienceDirect

Ultrasonics

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

An ultrasonic methodology for determining the mechanical and geometrical properties of a thin layer using a deconvolution technique

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ARTICLE INFO

Article history:
Received 8 December 2012
Received in revised form 3 April 2013
Accepted 3 April 2013
Available online 25 April 2013

Keywords:
Thin layer
Mechanical and geometrical properties
Normal reflection spectrum
Deconvolution

ABSTRACT

An ultrasonic method is proposed for simultaneously determining the thickness, density, sound velocity, and attenuation of a thin layer from a reflection spectrum at normal incidence. The normal theoretical reflection spectrum of a thin layer is established as a function of three dimensionless parameters to reduce the number of independent parameters. The inverse algorithm, using the least squares method, is adopted to determine the dimensionless parameters, and the corresponding convergence zones are investigated. The measured reflection spectrum at normal incidence is obtained using Wiener filtering, and spectral extrapolations following Wiener filtering are applied to obtain the time-of-flights by identifying the overlapping pulse-echoes inside the thin layer and the superposing pulse-echoes from the reference material and front surface of the specimen. The thickness of the thin layer can then be calculated and as initial estimate for the inverse algorithm. The density, sound velocity, and attenuation are then determined by the measured thin layer thickness and determined dimensionless parameters. Two 500 μm stainless steel and aluminum plates were immersed in coupling water and a 5 MHz flat transducer was applied. The relative errors of measured thickness, density, and sound velocity were less than 6%, and the ultrasound attenuation was close to its true value. The validity of the proposed technique was verified.

1. Introduction

There has been a growing scientific and practical interest in thin layers for applications in physics, engineering, and biology, and the importance of thin layers is rapidly increasing. It is well known that the mechanical and geometrical properties of a thin layer are depending on the thin layer microstructures; thus, the thickness, density, sound velocity, and attenuation of a thin layer that are sensitive to the defect and material properties, have been used to characterize thin layers. By applying ultrasound to realize non-destructive characterization, tone must inspect the mechanical integrity through a criterion that indicates the change of acoustic and geometrical properties of the material. For this purpose, the parameters including the thickness, density, sound velocity, and attenuation should be measured accurately, and their interactions need to be well established [1].

The ultrasonic techniques for characterizing thin layers usually can be classified into two categories: one is performed in the time domain, and the other in the frequency domain. However, in using ultrasound, a thin layer typically means that two successive pulse-echoes from the specimen are overlapping and interfering with each other, and thus cannot be separated in the time domain. Therefore, the pulse-echo method breaks down for measuring the properties of the thin layer in the time domain as normally incident reflected waves are the concern in this paper. Ultrasonic spectroscopy techniques based on spectral analysis have long been thought to be promising, and have been used successfully to characterize the thin layers immersed in water, or embedded between two known materials such as an adhesively-bonded joint. Kinra and Iyer developed a method to determine the properties of a thin layer from the normal reflection and transmission spectrum [2,3]. Every estimated thickness and density of the thin layer using low frequency through-transmission ultrasonic technique [4]. Zhao et al. simultaneously measured the thickness and longitudinal wave velocity of coating on thick substrate using reflection coefficient amplitude spectrum [5]. Tohmyoh et al. measured the acoustic impedance, velocity, and density of thin polymer films using a broadband transducer with a nominal frequency of 50 MHz [6]. However, in the aforementioned techniques, the main attention was given to measuring a single specific property of the thin layer. Hurley et al. presented a method to simultaneously measure the thickness, density, sound velocity, and attenuation of composite plates [7], but this method is limited to thick plates only, which means two successive pulse-echoes from the plates must be separated in the time domain. Applying ultrasonic spectroscopy

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http://dx.doi.org/10.1016/j.ultras.2013.04.006

techniques, the thin layer properties are usually determined by the inverse algorithm by minimizing the difference between the theoretical and the measured reflection spectrums, but the limitation is that the initial guesses for the inverse algorithm must be given within the convergence zones, and they are difficult to assign in practice because no prior knowledge is known. Moreover, the measurement of reflection spectrum at normal incidence is typically calculated and known using discrete Fourier transforms of specimen signal and the measurement system impulse response. This direct inverse problem makes the system very sensitive, and any slight fluctuation of noise or measurement error may have a significant impact on the measured results. Therefore, it is necessary to develop an ultrasonic method to overcome these limitations.

In this paper, we propose an ultrasonic method for simultaneously characterizing the thickness, density, sound velocity, and attenuation of a thin layer from a reflection spectrum at normal incidence. The theoretical reflection spectrum was established as a function of three dimensionless parameters in order to reduce the number of parameters. The inverse algorithm utilizing least squares method was described and the convergence zones of the dimensionless parameters when performing inverse algorithm were investigated, and found that one convergence zone of the dimensionless parameters which is related to the time-of-flight in the thin layer, is quite narrow. For the purpose of separating the overlapping pulse-echoes inside the thin layer and the superposing pulse-echoes from the reference material and specimen, a deconvolution technique combining Wiener filtering and spectral extrapolations is adopted. The reflection spectrum at normal incidence is obtained using Wiener filtering, and then spectral extrapolations following Wiener filtering are applied to derive the initial guesses and thin layer thickness according to the time-of-flights. The simultaneously characterizing thickness, density, sound velocity and attenuation of 500 μm stainless steel plate and aluminum plate by using the 5 MHz flat transducer were carried out. The results demonstrate that the relative errors of measured thickness, density, sound velocity are less than 6%, the sound attenuation is close to its true value. The validity of the proposed method is verified. The present work shows the high efficiency, viability and capability of the non-destructive technique and offers a new way to simultaneously characterizing basic mechanical and geometrical properties of thin layers.

2. Theoretical model

A three-layered structure composed of two known substrates and a thin layer is shown in Fig. 1, in which the acoustic impedance is denoted by $Z_i = \rho_i c_i$ (i = 1, 2 and 3) with ρ_i and c_i being its density and velocity, respectively. Considering the plane waves that are

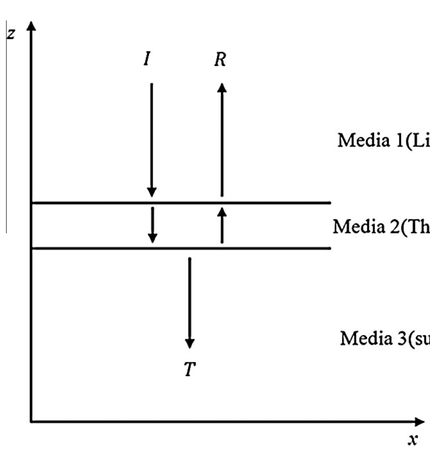

Fig. 1. The schematic of a three-layered structure.

normally incident, the theoretical reflection spectrum of thin layer is given by [8]:

$$X_c(\omega) = \frac{R_{12} + R_{23}e^{2ik_2d_2}}{1 + R_{12}R_{23}e^{2ik_2d_2}}, \tag{1}$$

where $k_2 = \omega/c_2$ is the wave number, d_2 is the thickness of thin layer, and $R_{12} = (Z_1 - Z_2)/(Z_1 + Z_2)$ and $R_{23} = (Z_2 - Z_3)/(Z_2 + Z_3)$ are the reflection coefficients at the front and back interfaces of the thin layer, respectively. For a viscoelastic layer, k_2 is complex impedance, i.e. $k_2 = k_2' + ik_2''$, and k_2'' is the frequency-dependent attenuation. From Eq. (1), it can be seen that $X_c(\omega)$ depends on four independent properties of the thin layer including thickness, density, sound velocity, and attenuation. To reduce the number of independent parameters, we introduce three dimensionless parameters. These dimensionless parameters are impedance ratio Z_n, dimensionless thickness h_N, and dimensionless attenuation α_I, defined as

$$Z_n = \frac{Z_2}{Z_1}, \tag{2}$$

$$h_N = \frac{d_2}{c_2}\omega_0, \tag{3}$$

$$\alpha_I = \frac{k_2''}{k_2'}. \tag{4}$$

where $\omega_0 = 1$ MHz is normalization constant. By introducing Z_n, h_N, and α_I, Eq. (1) can be rewritten as

$$X_c(\omega) = \frac{\left(\frac{1-Z_n}{1+Z_n}\right) + \left(\frac{Z_n - Z_3/Z_1}{Z_n + Z_3/Z_1}\right)\exp(2i\omega h_N(1 + i\alpha_I))}{1 + \left(\frac{1-Z_n}{1+Z_n}\right)\left(\frac{Z_n - Z_3/Z_1}{Z_n + Z_3/Z_1}\right)\exp(2i\omega h_N(1 + i\alpha_I))} \tag{5}$$

When the substrate 1 is the same as substrate 3, the theoretical reflection spectrum can be simplified as

$$X_c(\omega) = \frac{(1 - Z_n)/(Z_n + 1)(1 - e^{2i\omega h_N(1+i\alpha_I)})}{1 - ((Z_n - 1)/(Z_n + 1))^2 e^{2i\omega h_N(1+i\alpha_I)}}, \tag{6}$$

Thus, the theoretical reflection spectrum of the thin layer at normal incidence as a function of three dimensionless parameters and frequency ω is established.

To determine these dimensionless parameters, an inverse algorithm using the least squares method to minimize the sum of squared deviations between theoretical and measured reflection spectrums is adopted:

$$\min_{x \in \Re^3} \frac{1}{2}\sum_{n=1}^{N}(|X_e(x,\omega)| - |X_c(x,\omega)|)^2, \tag{7}$$

where N is the number of data points at different frequencies over the ultrasonic transducer bandwidth, $x = (Z_n, h_N, \alpha_I)$ is a parameter set that consists of the unknown dimensionless parameters, $X_c(\omega)$ is the theoretical reflection spectrum at normal incidence, and $X_e(\omega)$ is the measured reflection spectrum, which will be described in the following section.

3. The convergence problem of the inverse algorithm

The initial estimates of the parameter set x are required to be assigned within the convergence zones; otherwise, the search for the best estimate of x will either diverge or converge to an incorrect minimum. Therefore, it is necessary to investigate the convergence zones of each dimensionless parameter first, in order to assign the initial guesses appropriately.

Fig. 2 shows the convergence of Z_n, h_N, and α_I on normal reflection spectrum when performing the inverse algorithm. The calculations are done using parameters of a thin aluminum plate