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Simultaneous determination of wave velocity and thickness on overlapped signals using Forward Backward algorithm

J. Bustillo*, H. Achdjian, A. Arciniegas, L. Blanc

INSA Centre Val de Loire, Université François Rabelais de Tours, CNRS, GREMAN UMR 7347, Blois, France

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ABSTRACT

This paper presents a method to simultaneously determine the wave velocity and the thickness of an unknown sample in case of overlapped ultrasonic signals. Indeed, the determination of the time delay in an ultrasonic signal can be critical to allow the simultaneous characterization of parameters of the studied material, such as the thickness and the wave velocity. Therefore, a forward-backward algorithm is applied to the overlapped signal using a reference signal in order to retrieve the excitation signal. Firstly, the method is explained and a validation on synthetic signal is performed to observe its robustness. Secondly, a time retrieval is performed on real signals to determine thickness and wave velocity in aluminium plates. The results show that this method is suitable to simultaneously retrieve thickness and wave velocity, even for overlapped signals (up to 65%), with a discrepancy as low as 1%.

1. Introduction

Ultrasonic methods for material characterization are mainly used in industry because they are non-invasive and contactless. Fields of applications are very wide, such as sensors [1], microelectronics [2,3], forestry [4], room acoustics [5] or crack detection [6]. This characterization can be performed using frequency-domain or time-domain analysis [2,7–9].

The determination of the thickness and the wave velocity of a sample gives several information on its state. Indeed, the aging of the sample can cause a variation of the wave velocity due to appearance of cracks or elastic behavior modifications. When thickness is unknown, simultaneous determination of thickness and wave velocity is mandatory to obtain reliable results.

The frequency domain analysis is often more robust [10]. However, these methods often need modelling and inverse problem solving due to couplings with surrounding fluid or another layers which cause complex spectrum variations [2]. time-domain analysis is often faster but limited when an overlap is detected or when the signal is highly noisy.

For time-domain analysis, the determination of the time of arrival of two echoes is mandatory to simultaneously obtain the thickness and the wave velocity of the sample [11,12]. These methods are usually limited to samples wherein the propagation path is long enough to allow an echo separation. For thin samples, overlapped echoes have to be separated to estimate the time of arrival. Several researchers have proposed reconstruction methods based on modelling of the echoes, on signal optimisation [13], on signal modelling [14–16] or on signal shaping [7].

In this paper, a method based on the optimisation of the excitation signal is proposed. First theoretical background for thickness and wave velocity retrieval is presented. Then, the minimization procedure, called Forward-Backward algorithm [17,18], is described. It takes into account the sparsity of signals by using a $l1$-norm constraint. In order to validate the method, a numerical simulation is performed using synthetic signals having several noises and echo spacings. Finally, ultrasonic experiments are carried out on aluminium plates. Retrieval of excitation signals (with or without overlap cases) are used to calculate thickness and wave celerities.

2. Theoretical background

2.1. Thickness and wave velocity retrieval

The measurements are performed in immersion using the insertion-substitution method, as shown in Fig. 1. In this method, transducers are surrounded by the same fluid (water in our case) for all the measurements and so their transfer functions can be assumed to be constant [19].

$$A_{ref}(t) = h_e(t)*h_r(t)*e^{j\frac{\omega D}{c_w}}e^{-\alpha_w D}d_w(D). \quad (1)$$

The signal $A_{ref}(t)$ recorded in the reference medium depends on

* Corresponding author.
E-mail address: julien.bustillo@univ-tours.fr (J. Bustillo).

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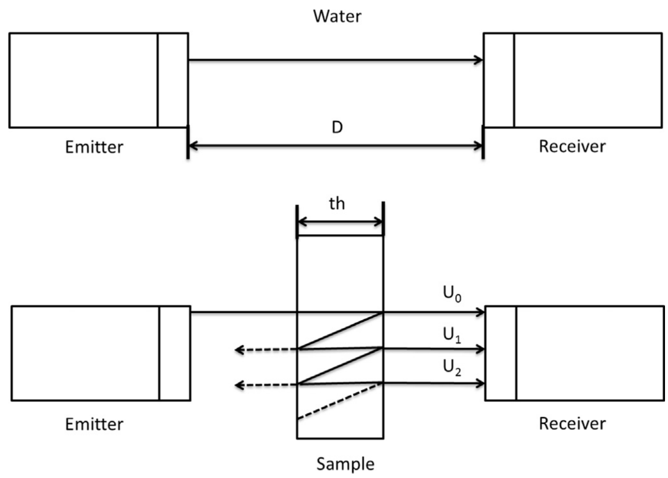

Fig. 1. Insertion/substitution principle: measurement in reference fluid (top) and after insertion of the sample (bottom).

the distance separating the transducers (D), the transfer functions of transducers ($h_e(t)$ and $h_r(t)$, respectively for the emitter and the receiver), the attenuation α_w in the fluid, the diffraction $d_w(D)$ and the wave velocity of the water c_w:

The Eq. (1) can be rewritten to take account the propagation through the layer corresponding to the sample and through the surrounding fluid:

$$A_{ref}(t) = h_e(t)*h_r(t)*\left(e^{j\frac{\omega(D-th)}{c_w}}e^{j\frac{\omega th}{c_w}}\right)(e^{-\alpha_w(D-th)}e^{-\alpha_w(th)})d_w(D), \quad (2)$$

where th is the sample thickness.

The sample thickness is small compared to the distance between transducers, so it can be assumed that the diffraction due to sample is negligible.

Therefore, we can define a transfer function $h_w(t)$ for the whole system, describing the transducer's transfer functions, the propagation through the surrounding fluid, the attenuation in surrounding fluid and the diffraction occurring in the fluid.

$$h_w(t) = h_e(t)*h_r(t)*e^{-\alpha_w(D-th)}e^{j\frac{\omega(D-th)}{c_w}}d_w(D). \quad (3)$$

Using this transfer function, the reference signal $A_{ref}(t)$ can be rewritten as:

$$A_{ref}(t) = h_w(t)*e^{-\alpha_w th}e^{j\frac{\omega th}{c_w}}. \quad (4)$$

When the sample is placed between the transducers, the ultrasonic wave propagates through the sample and the received signal depends on the acoustical and geometrical parameters of the sample. The ultrasonic signal has several echoes U_i due to the transmission/reflection of the ultrasonic wave at interfaces, as shown in Fig. 1. The received signal $A_s(t)$ is the sum of all these echoes:

$$A_s(t) = \sum_{n=0}^{\infty} U_n(t). \quad (5)$$

Amplitudes and time delays of these echoes depend on the sample parameters. The received signal can be written as:

$$A_s(t) = h_w(t)*T_{w-s}e^{-\alpha_s th}e^{j\frac{\omega th}{c_s}}\left(T_{s-w} + \sum_{n=1}^{\infty}\left(R_{s-w}T_{s-w}e^{-\alpha_s th}e^{j\frac{\omega th}{c_s}}\right)^n\right), \quad (6)$$

where the subscripts s and w stand respectively for sample and water, α_s is the attenuation in the sample, c_s is the wave velocity in the sample and T_{i-j} and R_{i-j} are respectively transmission and reflection coefficients at the interface between the media i and j:

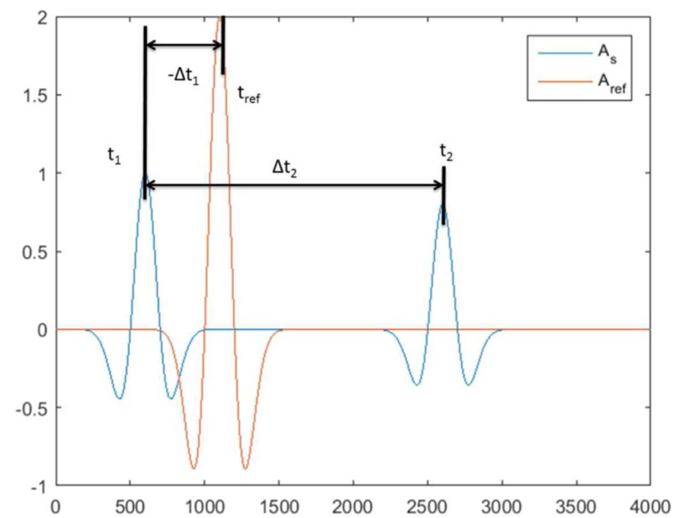

Fig. 2. Delays used for the simultaneous determination of wave velocity and thickness.

$$R_{i-j} = \frac{Z_i - Z_j}{Z_i + Z_j}, \quad (7)$$

$$T_{i-j} = \frac{2Z_j}{Z_i + Z_j}, \quad (8)$$

where Z_i is the acoustical impedance of the medium i, which is the product of the wave velocity and the volumetric mass density.

Using the signal A_{ref} and A_s, two different delays are defined: the delay Δt_1, between the echo of A_{ref} and the first echoes of A_s and the delay Δt_2, between the two first echoes of A_s, as shown in Fig. 2.

These delays allow to simultaneously determine the thickness (th) and the wave velocity of the sample (c_s), using the wave velocity in water (c_w) [7,12]:

$$th = \left(\frac{\Delta t_2}{2} + \Delta t_1\right)c_w, \quad (9)$$

$$c_s = \left(1 + \frac{2\Delta t_1}{\Delta t_2}\right)c_w. \quad (10)$$

When the echoes are overlapped, time delay measurements become difficult, and so the wave velocity and the thickness determination. A methods to overcome that using sparse signal recovery method, called Forward-Backward (FB) algorithm, is proposed in this paper.

2.2. Forward Backward algorithm

If the attenuation in the sample is small or comparable to the reference fluid attenuation, the echoes are similar to the reference signal. In order to simplify the sparse recovery, it is assumed that the echoes are identical to the reference signal. Therefore, the signal received through the sample can be written as a convolution of the reference signal $h_w(t)$ and of an excitation signal $e(t)$:

$$A_s(t) = h_w(t)*e(t) + n(t), \quad (11)$$

where $e(t)$ is the sum of Dirac delta functions:

$$e(t) = \sum_{i=1}^{\infty} \eta_i\delta(t - \tau_i). \quad (12)$$

τ_i and η_i are respectively the delays and the amplitudes of the echoes in $A_s(t)$:

A noise $n(t)$ is added to take account several errors due to the acquisition process. Then, Eq. (11) is rewritten in matrix form:

$$A_s = H_w E + N. \quad (13)$$

The simplest way to solve this kind of matrix is the Least Mean