Ultrasonics 73 (2017) 253–261

Contents lists available at ScienceDirect

Ultrasonics

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

Efficient algorithm for discrimination of overlapping ultrasonic echoes

Julien P. Fortineau [a,*], François Vander Meulen [a], Jérôme Fortineau [b], Guy Feuillard [b]

[a] *Université François Rabelais de Tours, GREMAN UMR 7347, 3 rue de la chocolaterie, 41000 Blois, France*
[b] *INSA Centre Val de Loire, GREMAN UMR 7347, 3 rue de la chocolaterie, 41000 Blois, France*

ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form 6 September 2016
Accepted 11 September 2016
Available online 12 September 2016

Keywords:
Overlapping
Time of flight
Matching pursuit

ABSTRACT

We propose a method to identify the different echoes of an overlapped ultrasonic signal. This method is based on an iterative algorithm that compares the experimental signal to a realistic dictionary of trial functions and allows identification of one overlapped echo at each iteration. Adding physical parameters to the dictionary such as sample attenuation and ultrasound beam diffraction allows the method to be applied to various materials and sample geometries. Measurements at 500 kHz and 5 MHz on a ABS material and a copper plate are reported. The effectiveness and the robustness of the method are studied as a function of time delay between the different echoes. We show that taking into account the experimental set-up and material properties in the development of the dictionary are critical to identifying a round-trip signal when overlapping occurs.

1. Introduction

Analysis of an ultrasonic wave which has transited through a sample allows the determination of several mechanical parameters of the sample [1,2]. Depending on the thickness of the sample and the center frequency of the transducers, two cases can be encountered in normal incidence. If the different echoes are not overlapped, temporal [3] and frequency [4,5] analysis are suitable to obtain sample characteristics such as thickness, attenuation and ultrasound velocity [6]. For a given pair of transducers, when the sample thickness decreases, overlapping of the multiple reflected echo occurs and conventional analysis is no longer possible. Increasing the transducer frequency and bandwidth can be an issue. However, when very thin materials need to be characterized (a few tenths of micrometer thick), using ultra high frequency transducers results in several difficulties: higher transducer costs, adaptation of the experimental setup and less penetration through the sample due to the attenuation.

Many signal processing methods have therefore been investigated to improve time resolution [8,9]. In many cases, these methods assume that the incident waveform is known and that its shape is similar to the different echoes. However, for highly attenuating or dispersive materials, or when diffraction effects cannot be disregarded, this assumption is not valid. To overcome this problems, sparse representation methods such as Fractional Fourier transform [10,11], Wavelet decomposition [12,13], Basis Pursuit [14,15] or the Matching Pursuit (MP) algorithm [16–18] have been introduced. With these methods, a signal is simulated using a large dictionary of elementary functions (atoms). The aim is to match the signal with a minimum number of atoms (sparsest representation). This produces effective results in finding the different echoes of an overlapped signal. Each echo is generally obtained by a combination of several atoms which have to be identified and labeled in a difficult process.

In this paper, an iterative algorithm adapted from the Matching Pursuit algorithm is presented that recovers the different echoes of an overlapped ultrasonic signal acquired from an insertion-substitution acoustic measurement. Here, one elementary function is added to the approximation at each iteration and each represents one echo as a consequence of the choice of the atom. Instead of using the Gabor function, the reference signal is used as the pattern of the atom. Development of the dictionary then includes the characteristics of the apparatus such as the electrical excitation, the frequency response of the transducers and the finite dimensions of the emitting and receiving transducers. Depending on the material, its attenuation and the diffraction effects of the ultrasonic beam can also be applied to the atom to improve the echoes identification. As in Mor et al. [19] the atom selection is performed in two steps in order to find a compromise between the reduction of the energy residue and the identification at each iteration.

After a rapid presentation of the insertion-substitution method, the key points of the Matching Pursuit algorithm are set out. The choice of dictionary is then discussed according to the physical characteristics of the sample used in the acoustic measurement. The method was applied to the ultrasonic characterization of an

---

[*] Corresponding author.
E-mail address: julien.fortineau@etu.univ-tours.fr (J.P. Fortineau).

http://dx.doi.org/10.1016/j.ultras.2016.09.010
0041-624X/

ABS (Acrylonitrile butadiene styrene) thermoplastic polymer immersed in water and its robustness was investigated as a function of the overlapping.

2. Insertion-substitution method

The insertion-substitution principle consists of comparing an ultrasonic signal between two transducers in a reference medium when the material under test is inserted [6,7]. Generally, to avoid multiple overlapping reflections, the time resolution is obtained using a broadband pulser.

The two transducers separated by the distance L1 + d + L2 are set up facing each other. L1 and L2 are the distances between the emitter transducer and the sample and between the sample and the receiver transducer, respectively and d is the thickness of the sample being characterized (Fig. 1).

The received signal depends on both the electrical and acoustic environment. The broadband signal U_R transmitted through the reference medium is expressed as:

$$U_R = Te^{-(\alpha_r+jk_r)d}D_r(\omega, L_1 + d + L_2) \tag{1}$$

$$T = E(\omega)A_E(\omega)e^{-(\alpha_r+jk_r)(L_1+L_2)}A_R(\omega) \tag{2}$$

where $E(\omega)$ is the frequency response of the electrical pulser, and $A_E(\omega)$ and $A_R(\omega)$ the frequency responses of the emitter and the receiver, respectively. $D_r(\omega, L_1 + d + L_2)$ is the diffraction term of the ultrasound beam in the reference medium corresponding to the distance $L_1 + d + L_2$. α_r is the attenuation coefficient in Np/m and k_r the wave number. The subscript r denotes the reference medium.

Multiple reflections appear when the sample is inserted perpendicular to the transducers' axis (Fig. 1b). The received signal, U_T, is composed of different echoes U_i and can be written:

$$U_T = \sum_{i}^{N} U_i \tag{3}$$

which can be rewritten expressing the multiple path as :

$$U_T = TT_{rm}T_{mr}e^{-(\alpha_m+jk_m)d}\sum_{i=1}^{N}\left(R^2e^{-2(\alpha_m+jk_m)d}\right)^{i-1}D_m(\omega, L_1, d\cdot(2i-1), L_2) \tag{4}$$

The subscript m denotes the sample. T_{rm} and T_{mr} are the transmission coefficients between the reference medium and the sample and between the sample and the reference medium, respectively. A decrease in amplitude ($R^2e^{-2\alpha_m d}$) and a delay appear between the successive echoes, U_i, as a consequence of the impedance mismatch between the reference medium and the sample and of back and forth propagation paths. The time delay, Δt, between the reference and the first transmitted echo can be written as:

$$\Delta t = d\left(-\frac{1}{v_m} + \frac{1}{v_r}\right) \tag{5}$$

where v_m is the ultrasonic wave velocity in the sample and v_r the ultrasound velocity in the reference medium.

The time delay, Δt_{12}, between the first and the second echo can be written:

$$\Delta \boldsymbol{t}_{12} = \frac{-2 * \boldsymbol{d}}{\boldsymbol{v_m}} \tag{6}$$

If there is no overlapping between the first and second echoes, these two time delays can be found by classical Time of Flight measurements such as cross correlation, and several properties such as the material velocity and thickness can be deduced.

3. Matching pursuit

Proposed independently by Mallat and Zhang [16] and Qian and Chen [17], the Matching Pursuit algorithm enables signal decomposition as a linear combination of elementary functions (atoms) that are selected from a dictionary.

The correlation between the atom, $g(t)$, and the signal, $f(t)$, each sampled at M discrete times, is the scalar product of these two functions [16]:

$$\langle f, g\rangle = \sum_{i=1}^{M} f(t)g^*(t) = Ae^{j\phi} \tag{7}$$

where $g^*(t)$ is the complex conjugate of $g(t)$. A is the coefficient which shows the degree of correlation between the signal and the real waveform associated with the elementary functions at the ϕ phase. At each iteration the atom which has the highest A magnitude is selected by the algorithm. The waveform associated with this atom is then subtracted from the signal. The residual signal becomes the signal to be fitted at the next iteration. As a result, the algorithmic method allows maximum decrease in the energy residue r_2 at each iteration:

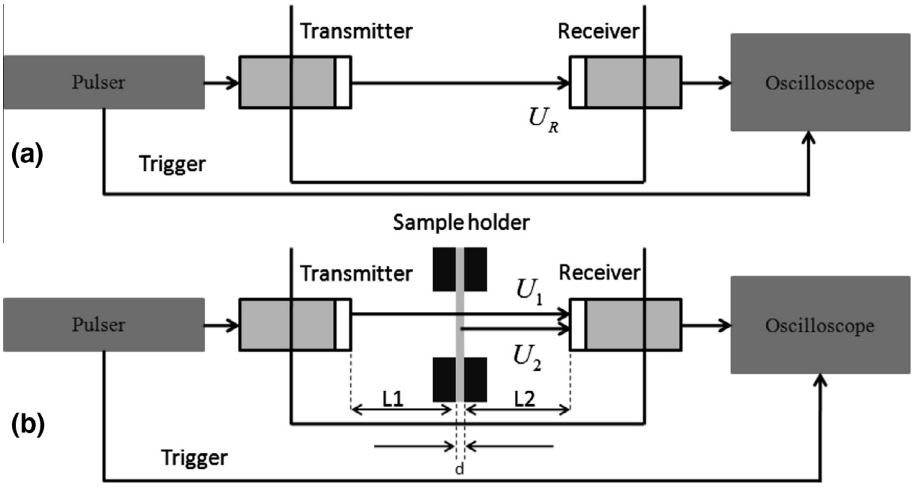

Fig. 1. Principle of the insertion-substitution method. (a) Acquisition of the reference signal, (b) acquisition of the signal through the sample.