Ultrasonics 65 (2016) 315–328

Contents lists available at ScienceDirect

Ultrasonics

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

Layered material characterization using ultrasonic transmission. An inverse estimation methodology

María G. Messineo [a], Guillermo Rus [b], Guillermo E. Eliçabe [c], Gloria L. Frontini [a,c,*]

[a] Department of Mathematics, Engineering School, National University of Mar del Plata, Mar del Plata, Argentina
[b] Department of Structural Mechanics, University of Granada, Spain
[c] INTEMA-CONICET Material Science and Technology Research Institute, Mar del Plata, Argentina

ARTICLE INFO

Article history:
Received 26 May 2015
Accepted 16 September 2015
Available online 28 September 2015

Keywords:
Ultrasound
Layered materials
Inverse problem
Parameter estimation
Mechanical properties

ABSTRACT

This paper presents an inverse methodology with the aim to characterize a layered material through the identification of acoustical and mechanical properties of its layers. The framework to accomplish this objective is provided by the Inverse Problems (IPs) theory. Material characterization refers to the detection and localization of discontinuities, as well as to the identification of physical properties, in order to predict the material behaviour.

In this particular case, the IP is solved in the form of a parameter estimation problem, in which the goal is the estimation of the characteristic acoustic impedance, transit time, and attenuation of each layer. These parameters are directly related to relevant material properties, such as the speed of sound, density, elastic modulus and elastic energy dissipation constants. The IP solution is obtained by minimizing a cost functional formulated as the least squares error between the waveform calculated using an equivalent model, and the measured waveform obtained from ultrasonic transmission tests.

The applied methodology allowed the accurate estimation of the desired parameters in materials composed of up to three layers. As a second contribution, a power law frequency dependence of the wave attenuation was identified for several homogeneous materials, based on the same ultrasonic transmission experiments.

1. Introduction

This paper presents a methodology to characterize layered materials solving an Inverse Problem (IP), based on an idealized model of the physical problem and using data obtained from ultrasonic wave transmission measurements.

Layered materials are a particular sort of composites, where the layers can be made of homogeneous materials, like polymers, metals or ceramics, or can be composed of fibber or particle reinforced materials [1,2]. In the course of time, more and more applications require the use of composites, which combine different materials properties in order to fulfil specific characteristics. Therefore, the study of composite materials is of great importance for the evaluation of their performance and for monitoring their properties.

Structures that can be studied like layered materials can be also found in nature. Rocks, dental pieces, bones, or other biological tissues (skin, fat, muscle) [3,4] are examples of these structures. In particular, in the case of biological tissues the detection and localization of the mechanical changes that suffer the structure when affected by pathology are the basis of many diagnosis tools.

Some methods widely used to identify material properties usually involve destructive testing, such as film indentation [5] or tensile tests [6], from which the values of the elastic constants can be inferred, based on the fitting to experimental curves. However, quantitative non-destructive evaluation (NDE) techniques are necessary to perform remote tests or whenever we need to assure the integrity of the analyzed piece, i.e., when the studied sample is on its service period or when it is a living tissue.

NDE techniques include, along with the selection of the measurement techniques, the experimental setup, the validation of physical models and the reliability of the computational methodology. The measurement technique chosen to carry out the tests in this work is ultrasound, high frequency acoustic waves capable to inspect both, solids or liquids. Ultrasound is used typically in the detection of defects, cracks, pores, or any lack of continuity in the sample. However, a more advanced use of this technique, since it involves a more sophisticated analysis of data, is the

* Corresponding author at: Department of Mathematics, Engineering School, National University of Mar del Plata, Mar del Plata, Argentina.
E-mail addresses: gmessineo@fi.mdp.edu.ar (M.G. Messineo), grus@ugr.es (G. Rus), elicabe@fi.mdp.edu.ar (G.E. Eliçabe), gfrontin@fi.mdp.edu.ar (G.L. Frontini).

http://dx.doi.org/10.1016/j.ultras.2015.09.010
0041-624X/

identification of acoustical and mechanical properties of the material, the interest of this work.

Amongst the works that are based on ultrasonic NDE techniques, the determination of the acoustic impedance profile reported in [7] is one of especial interest. The data is the reflection impulse response of the ultrasonic wave, considering that the transducer response and the medium attenuation are known. The proposed application is the detection of plaque formation in the arteries using layered phantoms of liquid layers separated by thin polymeric membranes as test objects.

Ultrasound is frequently used to evaluate biological materials considered as layered structures. Leite et al. [8] perform a theoretical and computational study of ultrasonic wave propagation through three layers: fat, muscle and bone. This structure is of particular interest in therapeutic applications, especially at the interface muscle–bone, where excessive heating can occur during ultrasound therapy in soft tissues.

The complex nature of ultrasonic waves has led in recent decades to devote large amount of resources to study the theoretical and numerical aspects of the physical problem of wave propagation [9,10]. Methods to analyze and simulate the generation, propagation and interactions of a wave in a medium have been developed [11–13]. The Finite Element Method (FEM) or the Boundary Element Method (BEM), are proved and robust techniques that can be used to predict and visualize the wave propagation in structures with diverse geometry and complexity [14]. The limitation of these methods lies in the time required to process the code, related to the high resolution both, spatial and temporal, necessary to accurately represent the propagation of an ultrasonic wave.

Considering certain assumptions, the test to carry out the intended characterization can be well represented by equivalent models. In this paper, a model formulated in the frequency domain based on a transmission line (T-line) is used [15]. The model allows the determination of mechanical stresses at the interfaces of the samples, which using the electrical–mechanical analogies correspond to the electric tensions in a transmission line cascade. The same model was used in [16] to represent the propagation of an ultrasonic wave through a dental piece, composed by successive layers: enamel, dentin, pulp. The use of an equivalent model may be appropriate when it comes to optimize the computational resources. In this particular case, the transmission line model gives the possibility to represent the wave propagation through a layered material without numerically solving any differential equation. This feature provides an excellent computational efficiency. The disadvantage of these models is that they usually have restrictions that the real physical problems not always fulfil; therefore the obtained results may have errors.

Due to the complexity of the physical models that represent the studied situation it becomes necessary a direct comparison of the experimental data with the theoretical results, given by the solution of the so call forward problem. The IP provide a resolution framework for this sort of situations. Previous works have followed this approach. For instance, in [17] a method is presented to evaluate damage in Carbon Fibbers Reinforced Polymers (CFRP), which are widely used in industry, especially in aeronautics and automotive industries, due to its excellent relation weight-resistance. The evaluation is accomplished solving an IP to identify mechanical properties that allows monitoring the structural health of a piece for damage assessment or quality control. The datum is the waveform recorded at the end of the material in a transmission test [18,19], and the model used to represent the physical problem is an equivalent model based on the Transfer Matrix Formalism [20].

Hägglund et al. [21] carry out an integrity evaluation of an adhesive layer between two Pyrex dishes. They use an ultrasonic pulse-echo test, and the information contained in the measurements allowed obtaining a set of parameters from a maximum likelihood estimator.

Another application of ultrasound in biological tissues is found in [14], where Rus and García-Martínez dealt with the adhesion of nanostructured TiO_2 orthopaedic implants. An IP is solved to characterize the elastic modulus of each layer using FEM for the physical problem.

As addressed, the transmission line model is used in this work to represent the forward problem; the following two sections contain its description. Parameter estimation IP, formulated as the minimization of the least squares error between the experimental data and the theoretical functions obtained from the transmission line model, is introduced in Section 4. Also in this section, the proposed numerical resolution methodology based on one previously developed [22], is summarized.

In order to take into account the effect of wave attenuation, a thorough analysis performed based on the solution of the IP obtained using simulated measurements is reported in Section 5. In this section, the robustness of the methodology under modelling errors was also considered.

Finally, in Section 6 the inverse methodology was validated using experimental measurements. As a result, a set of parameters related to acoustic and mechanical properties of the layers of several materials could be identified.

2. The physical problem and the equivalent model

Ultrasound testing consists, generally, in recording the response generated by the propagation of an ultrasonic wave through a medium, either to detect discontinuities or to accomplish material characterization. Waves can take different modes, according to the particle oscillation direction and the wavefront geometry. A plane wave is one in which all the material particles oscillating in phase are on the same plane, and the oscillations can be longitudinal (P-wave) or transversal (S-wave) to the propagation direction.

P-wave propagation in an elastic, homogeneous, isotropic and non attenuating medium can be studied in one direction, and it is represented by the one-dimensional wave equation:

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2}, \tag{1}$$

where $u(x, t)$ is the particle displacement and c is the speed of sound in the medium.

The proposed methodology to carry out the material characterization in this paper is based on an equivalent model which represents the propagation of P-waves, and allows obtaining the exact solution of the wave equation (Eq. (1)) in two points of a homogeneous material [15]. This model is derived from the electrical–mechanical analogies between voltage, V, and mechanical stress, σ, and between electric current, i, and particle velocity, v.

The equivalent model implies a significant idealization of the physical problem, since rarely waves present in the material are only P-waves. For instance, discontinuities or changes in consistency can affect the wave causing phenomena such as scattering, reflection, diffraction or mode conversion. Nevertheless, a variety of real situations can be well represented by this model, as we analyzed in a previous work [22]. We simulated the ultrasonic P-wave transmitted through a layered material using both, the equivalent model and FEM and evaluated the accuracy with which the equivalent model reproduces the physical problem. Furthermore, this comparison allowed verifying the improvement in the computational efficiency introduced.

A material composed by N homogeneous layers, of thickness d_i and density ρ_i, can be represented by a cascade connexion of N transmission lines (T-lines) as shown in Fig. 1, where