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A high accuracy ultrasonic measurement system using the prism technique

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ABSTRACT

In this paper, a non-destructive measurement system is proposed to evaluate the elastic properties of highly attenuating homogeneous and non-homogeneous materials. This measurement system is based on a mode conversion technique allowing the evaluation of both compressional (P) and shear (S) waves with only one transducer. In the experimental investigation, the specimen under test (SUT), realized in a prism-shaped form, is tested using the prism technique. Then, the gathered backscattered echoes are estimated using a model-based estimation algorithm in order to extract the desired elastic properties. Accordingly, the estimated parameters are in good agreement with the manufactured values, which demonstrates the effectiveness of the proposed measurement system, and therefore, can be considered as a promising way to robustly evaluate certain properties of highly attenuating materials.

1. Introduction

In ultrasonic non-destructive testing (NDT), a common goal is to determine the relationship between the structure of a material and its properties. Generally, there exist a variety of ultrasonic NDT techniques such as pulse-transmission, pulse-echo, impact-echo and many others [1,2]. In particular, the pulse-echo technique is known to be as one of the simplest and effective methods for testing materials in a non-destructive manner. In this technique, echoes are generated and recorded using the same transducer, and then analyzed to extract some physical characteristics of the SUT. Specially, the strength of a material is determined from ultrasonic velocities of compressional and shear waves, corresponding to multiple reflected echoes.

Several works have been dedicated to studying the correlation between ultrasonic wave velocities and physical characteristics of homogeneous and non-homogeneous materials. Voigt and Shah [3] developed a shear wave reflection method to monitor the hydration kinetics of Portland cement mortar. This method measures the reflection loss of shear waves at an interface between a steel plate and the mortar. Ye et al. [4] proposed an ultrasonic experimental set-up to monitor the development of the micro-structure of fresh concrete at different temperatures. The ultrasonic pulse velocity has proved to be effective when determining both the micro-structure and strength of concrete at early stage. Kahraman et al. [5] developed a quality classification system of building stones from P-wave velocity and its application to stone cutting with gang saws. In this context, the authors realized that the quality classification and estimation of slab production efficiency of the building stones can be made by ultrasonic measurements. Bouhadjera and Bouzrira [6] proposed an intuitive measurement technique, called the prism technique, which has been successfully employed to evaluate the elastic properties of highly attenuating materials. It has also been demonstrated that this measurement technique can preserve consistent amplitude of all reflected echoes regardless the time of flight [7]. Further, the prism technique has been adopted to construct the spectral image of the pulse-echo tests while using the elastodynamics finite integration technique (EFIT) [8]. The results that have been obtained so far are very encouraging since they show the effectiveness and importance of the developed prism technique while estimating ultrasonic parameters of homogeneous and non-homogeneous attenuating materials. Of course, the prism technique has been successfully employed to evaluate the elastic properties of highly attenuating materials. However, in this method, measurements are made in three steps which require almost exact knowledge of the first and second critical waves of the specimen under test (SUT). These three steps are: (i) We need to make a measurement at normal incidence (angle of incidence equal to zero) which will provide information on the reflection from the front face (first echo). (ii) The angle of incidence is increased using very small variations until the first echo disappears and a second echo appears which corresponds to the longitudinal wave. We not that there are other echoes which also appear, and hence, the risk of not choosing the right echo is strong unless we have an idea about the type of the chosen SUT. (iii) The angle of incidence is increased again until the second echo disappears and a third echo appears. This echo will be considered as the transverse wave. Note also that the same

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problem as for the longitudinal wave can be revealed: information about the SUT, the critical angles and the good choice for the angle of incidence.

On the other hand, the estimation of ultrasonic backscattered echoes is a delicate task. Various model-based estimation algorithms have been developed to extract the ultrasonic parameters from these backscattered echoes. Some model-based estimation algorithms translated the estimation process of complicated superimposed echoes into isolated echo estimation. Ziskind and Wax [9], e.g., developed an effective algorithm to measure superimposed signals using the maximum likelihood estimation (MLE) principle of multiple sources by alternating projection. Demirli and Sanii [14,11] proposed an algorithm based on expectation maximization (EM) principle to estimate ultrasonic signals in term of Gaussian echoes. In [12], Martinsson et al. proposed an intuitive method that enables complete post-separation of measured superimposed signals. This method is based on a combination of hard physical and soft empirical models in order to describe both known and unknown properties, and hence, making a complete separation of the backscattered echoes. Kim [13] developed an alternative approach which uses the least mean square (LMS) method, the expectation maximization algorithm, and the model-based deconvolution principle to classify the non-destructive evaluation signals from the steam generator tubes in a nuclear power plant.

In view of the above discussion, the aim of this study is to develop a non-destructive measurement system to evaluate the elastic properties of attenuating homogeneous and non-homogeneous materials. This proposed measurement system consists of two phases. The first phase concerned the experimental investigation such that the SUT, realized in a prism-shaped form, is tested using the prism technique. After that, the collected backscattered echoes are estimated using a model-based estimation algorithm. Since these echoes can be modeled in terms of superimposed Gaussian echoes, then, the expectation-maximization algorithm is well suited in order to extract the desired ultrasonic parameters. In fact, it has been shown that this algorithm can perform even if the superimposed Gaussian echoes are corrupted by additive white Gaussian noise (AWGN) with high signal to noise ratio (SNR) [11]. The main contribution of this work is that, both P and S-wave velocity parameters, which characterize the strength of attenuating materials, are simultaneously estimated in the same experimental manipulation according to a selected angle of incidence. Hence, we can note the following improvements for the proposed measurement system: (i) The measurement is made in one experiment, in the sense that the backscattered echoes contain the front echo, the longitudinal wave and the transverse wave. This can be of great interest since only one experiment allows determination of the different echoes without worrying about the type of the SUT. (ii) The angle of incidence is generally pseudo-random, and therefore, it can be chosen such that the backscattered echoes are displayed in the same measurement. Finally, experimental results are provided to show the effectiveness of the proposed measurement system.

In order to achieve the proposed goals, this paper is organized as follows: Section 2 gives the background theory of the reflection and transmission coefficients, and the Gaussian echo model (GEM); Section 3 presents the developed non-destructive measurement system including a representation of the experimental set-up and a description of the expectation-maximization algorithm to estimate the ultrasonic superimposed backscattered echoes; Section 4 presents the obtained results when using the developed system in two specific case studies; and finally, Section 5 draws the conclusions.

2. Theoretical backgrounds

2.1. Gaussian echo model

The Gaussian echo model (GEM) is used as an elastic source time function to model the backscattered echoes [14,15]. It is given by

$$S(\theta;t) = Ae^{-\alpha(t-\tau)^2}\cos(2\pi f_c(t-\tau) + \varphi), \tag{1}$$

where $S(\theta;t)$ is the Gaussian echo, and the vector $\theta = \{A;\alpha;\tau;f_c;\varphi\}$ is the ultrasonic vector of the GEM related to the physical properties of the investigated material; whereas A is the amplitude of the signal, α is the bandwidth factor, τ is the arrival time, f_c is the center frequency. Note that these parameters are governed by the transducer frequency characteristics and the propagation path. Finally, the parameter φ represents the phase of the signal which accounts for the distance, impedance, size and orientation of the reflector.

Since the backscattered echoes are generally corrupted by additive noise, the GEM is rewritten as follows

$$x(\theta,t) = S(\theta;t) + w, \tag{2}$$

where $S(\theta;t)$ is the GEM given by Eq. (1), $x(\theta,t)$ is the GEM corrupted by noise, and w is the AWGN with variance σ^2 and mean zero.

2.2. Prism technique

The prism technique, developed by Bouhadjera and Bouzrira in [6], is based on a mode conversion technique. This method involves measuring the velocity of both compressional and shear waves in prism-shaped specimens with only one transducer. Accordingly, both compressional and shear waves were generated within the specimens through mode conversion. The angle of incidence must be chosen with high accuracy, thus increasing the efficiency of the measuring system. In fact, an adequate angle of incidence must be selected in order to collect multiple backscattered echoes in one measurement manipulation. Fig. 1 shows a simple form of the SUT in a prism-shaped form. The theoretical results of the prism technique have demonstrated that it is possible to evaluate the velocities of ultrasonic P and S waves using the following formula [6]:

$$c_{P,S} = \frac{a}{T_{P,S}-t_1}, \tag{3}$$

where a represents the side of the prism, $T_{P,S}$ represent the arrival times for the P and S waves, respectively, which are extracted from the backscattered echoes, and t_1 corresponds to the total reflection from the main face of the SUT, which occurs when the angle of incidence is equal to zero. On the other hand, the Lamé's constants are calculated from the following two equations:

$$\lambda = \rho(c_P^2-c_S^2), \quad \mu = \rho c_S^2, \tag{4}$$

where λ is the Lamé's coefficient, μ is the shear modulus and ρ is the density. Therefore, it is possible to calculate the Young's modulus E and Poisson's ratio σ according to the following formulas:

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} = \rho c_s^2\frac{3c_p^2-4c_s^2}{c_p^2-c_s^2}, \tag{5}$$

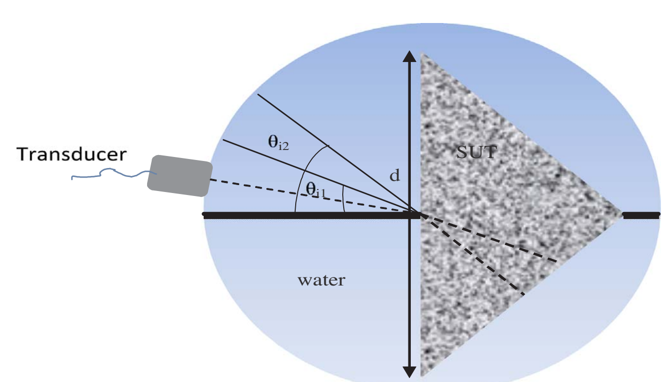

Fig. 1. The prism technique [6].