Mechanical Systems and Signal Processing 108 (2018) 238–251

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Robust non-destructive measurement system for extraction of ultrasonic wave parameters using the prism technique

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A R T I C L E I N F O

Article history:
Received 18 April 2017
Received in revised form 4 February 2018
Accepted 13 February 2018

Keywords:
Ultrasonic
Non-destructive evaluation
Elastic properties
Prism technique
Matching pursuit method
Genetic algorithms

A B S T R A C T

In this paper we propose a measurement system to evaluate the elastic constants of materials using only one experiment. This measurement system is based on the ultrasonic prism technique for the nondestructive measurement of both compressional and shear waves, and on the matching pursuit combined with genetic algorithms (MP-GA) to estimate these two backscattered echo waves. Under this framework, samples are realized in prism-shaped forms using a special molding box. Then, the MP-GA method is used to derive the time of flight of the measured data by a deconvolution process. The backscattered echoes are constructed using a parametric model-based vector for which the corresponding parameters are closely related to the physical properties of the ultrasonic signal propagating through the investigated material. The effectiveness of the measurement system is approved by estimating the elastic properties of homogeneous and non-homogeneous solid materials. Further, several tests have shown that this measurement system works well even for low SNR levels.

1. Introduction

One of the most interesting applications of ultrasonic non-destructive evaluation (NDE) is the estimation of elastic constants of materials. The main advantage of ultrasonic NDE is its non destructive and non invasive nature, and thus the opportunity to measure a large class of materials [1]. On the basis of the mode propagation, there are four types of ultrasonic velocities: the compressional, shear, surface and lamb wave velocity. Compressional and shear waves' velocities are most often used in ultrasonic inspection of materials because they are closely related to the elastic constants and density. In this context, several methods have been developed since many years to assess the quality of materials. Nigro and Huang [2], e.g., have proposed an estimation technique to determine the elastic constants of anisotropic solids from experimental results. This technique has proved to be useful while estimating the elastic properties of this type of materials, however, it requires samples cut in various directions to allow access to all constants, which is difficult to manufacture or even impossible in some cases. Estimation of elastic constants by ultrasonic immersion tests is an alternative concept mostly based on the measurement of the time of flight (TOF), time of flight diffraction (TOFD) or the time difference of arrival (TDOA) of ultrasonic waves. In particular, the time of flight is used to calculate the phase velocity and the refraction angle in the samples. Castellano et al. [3] have developed a goniometric ultrasonic non-destructive method to determine the elastic constants of a transversely isotropic unidirectional composite. The experimental analyses have been supported by numerical simulations. However, most of the measurement systems using ultrasonic immersion tests are difficult to implement due to the lack

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https://doi.org/10.1016/j.ymssp.2018.02.026

of a clearly defined incidence angle of the ultrasonic wave. Bouhadjera and Bouzrira [4] have proposed an intuitive non-destructive technique, namely the prism technique to evaluate the elastic properties of highly attenuating materials. This technique involves the precise measurement of the TOF at fixed intervals of both compressional and shear waves using a high-frequency ultrasound. Latter, Bouhadjera and his collaborators [5,6] have successfully applied the 2-D elasto-dynamic finite integration technique to simulate the elastic wave propagation in the samples. Accordingly, simulation and experimental results have shown that the prism technique is a promising technique when compared with traditional goniometer and rotating plate techniques. So, the potential of this technique should be more exploited in a more efficient way, and the quality of measurement should be fully addressed. In fact, some errors may occur when determining the exact values of the TOF since this latter is picked directly from the digital oscilloscope. Note that small errors in these values can yield enormous deviations of the estimated waves' velocities from the real data, and thus in the resulting elastic constants values. To this end, a powerful signal processing technique is required to deal with the estimation of the TOF.

On the other hand, we are generally faced with noisy measurements while estimating the TOF of ultrasonic backscattered echoes, where the noise is caused by reflections on microstructures of the tested material and electronic disturbances. It is therefore desirable to remove these effects from the recorded signal using a suitable estimation algorithm. Various model-based estimation algorithms have been developed in the literature to extract the ultrasonic parameters from the backscattered echoes. Some model-based estimation algorithms translated the estimation process of complicated superimposed echoes into isolated echoes estimation. Ziskind and Wax [7] have presented an effective algorithm, known as SAGE algorithm, based on the maximum likelihood estimation (MLE) principle. Demirli and Sanii [8,9] have developed a parametric model for the estimation of backscattered echoes in term of Gaussian echo model, where the parameter vectors are estimated using the expectation maximization (EM) algorithm. However, Chung and Böhme [10] have noticed that the EM algorithm converges very slowly, and that the SAGE algorithm converges faster than EM under certain conditions but becomes unstable for low SNR levels. Moreover, these two algorithms do not guaranty convergence to the desired optimum. In [11], Martinsson et al. have proposed an ultrasonic estimation 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 materials properties, and hence, making a complete separation of the backscattered echoes. Kim [12] has presented an alternative approach which uses the least mean square, the EM algorithm, and the model-based deconvolution principle to classify the NDE signals from the steam generator tubes in a nuclear power plant. Recently, Bobman et al. [13] proposed two sparse deconvolution methods for ultrasonic non-destructive testing (NDT) for flaw detection in steel. The first method uses the matching pursuit algorithm in order to deconvolve the mixed data, and thus to remove the unwanted noise. The second method is based on the approximate Prony method. Both methods employ the sparsity assumption about the measured ultrasonic signal as prior knowledge. Particularly, the authors have considered the estimation of the TOFD for inspection of weld defects and the time of arrival for measuring back wall deformations. More recently, Rodriguez et al. [14] developed an intuitive method for automatic and simultaneous measurement of the phase velocity and thickness for thin composite plates materials on the basis of Ping He's method, cross-correlation functions and iterative deconvolution for accurate measurement of times of flight and gating. Experimental investigations have demonstrated that this method can be implemented automatically, thus yielding more accurate results.

In this paper, we consider the general optimization problem for automatic estimation of the ultrasonic elastic constants of materials. The originality of the proposed measurement system is that the velocities of compressional and shear waves are measured in only one step using the prism technique and an efficient algorithm based on matching pursuit based genetic algorithm. The matching pursuit (MP) method is used to extract the characteristic parameters of the ultrasonic NDT signal. The genetic algorithm (GA) is applied to optimize the elements of the MP method. For this purpose, we assume that the backscattered echoes are modeled using Gaussian echo functions to approximate the received signal. Hence, we construct a model parameter vector for which the corresponding parameters are closely related to the physical properties of the ultrasonic signal propagating through the investigated material. The obtained results are estimated vectors that contain only the most significant information about the original backscattered echoes. Experimental results are obtained using standard ultrasonic non-destructive testing devices. For our special applications, we have addressed the numerical experiments to ultrasonic NDE of three different materials to validate the effectiveness of the proposed measurement system. Computer and laboratory results show that this measurement system works well even at low SNR levels.

The rest of this paper is organized as follows. Section 2 presents the background theory on the ultrasonic wave propagation in materials and the Gaussian echo model (GEM). A review of the ultrasonic prism technique is provided in Section 3. The proposed model based estimation algorithm for the extraction of the elastic properties is described in Section 4. Section 5 provides simulation results of the estimated echo model for computer simulated signals with different SNR levels. Experimental results for three different specimens, i.e., aluminum, cement-paste, and mortar are investigated in Section 6 to validate the effectiveness of the proposed measurement system. In Section 7 some conclusions are drawn.

2. Theoretical background

2.1. Reflection and transmission coefficients at a fluid-solid interface

Fig. 1 shows how a plane wave is reflected and transmitted at an interface between fluid (with density ρ_f and P-wave velocity c_f) and solid (with density ρ_s, P-wave velocity c_p and S-wave velocity c_s). Reflected and transmitted waves' direc-