Estimation of ultrasonic wave parameters in materials under bending force

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Abstract—this paper presents the use of prism technique to determine the longitudinal and transversal wave parameters in materials under simple bending forces. The weak number of studies on acoustoelastic behavior and the evolution of measurement methods led us to propose a complete feasibility study on measurements of longitudinal and shear waves for different mediums subjected to uniaxial compressive stresses.

The expectation maximization algorithm is employed for parameters estimation those are amplitude, phase, time of flight, frequency and bandwidth. These parameters allow the verification of the parameter values modification resulting from the effect of bending stresses.

Keywords—ultrasonic; prism technique; expectation maximization algorithm.

I. INTRODUCTION

The materials have a certain resistance to the passage of the ultrasounds. This resistance known under the name of impedance is really a function of the modulus elasticity and the material density. The impedance value changes from one material to another and the difference between two materials constitutes what is called an interface. As in optics, each time that an aural signal meets an interface, part of incidental energy is transmitted about the second medium, while the other part is reflected, while holding account that the directions of the transmission and the reflexion depend on the incidence angle and the sound wave [1]. At the time of the reflexion, energy thus reflected (echo) is used to identify, locate and characterize the interface between two mediums. In the world of the ultrasounds, the ultrasonic waves constitute an average privileged person of investigation in the study of the mechanical behavior of materials, as well as the analysis and the characterization of the mechanical properties of these materials. Allowing the measurement of the elastic constants for the second and third order, the measurement techniques of ultrasonic wave’s propagation velocities knew a very significant evolution last years, and several devices of measurement were elaborate in this direction. But the majority as of these methods presents a considerable disadvantage which is the complexity of the measurement system.

II. THEORETICAL BACKGROUND

A. Prism technique

The prism technique was developed by Bouhadjera [2]. The main piece of this technique is the transducer cell represented in Fig. 1. It consists of a cylindrical platform upon which the specimen under test (SUT) is fixed. The single transducer that acts as both transmitter and receiver is put on a ring that turns around SUT with a radius $R$. The ultrasonic beam makes an angle $\alpha$ that varies in a continuous manner from $0^\circ$ to $90^\circ$. The main face of SUT is put against the diameter line $XX'$. Total reflection from the main face of SUT occurs when the angle $\alpha$ is equal to zero. This enables the evaluation of time-of-flight $t_1$. By increasing the angle, the first echo disappears, and a second echo that is relatively smaller appears, which is related to refracted compressional waves within SUT. The position of this echo is independent of the angle $\alpha$, but its amplitude varies with varying the angle during the time of experiment, which takes a couple of minutes. It is worth noting here, that both the amplitude and the position of the echo would also shift, if the experiment drags for a long period, because of the changing properties of the material with time. When the maximum amplitude is reached at a certain angle, it can fall back to half its value by increasing or decreasing the angle by about $6^\circ$. A further increase of the angle makes the second echo disappear, and after that a third echo will appear, which is related to shear waves. Time-of-flight $T_{CS}$ is measured from these last two echoes for both longitudinal and transverse waves, respectively.

Figure 1: Transducer-cell configuration
B. Expectation-maximization estimation algorithm [3]

The Expectation-Maximization (EM) algorithm is a popular numerical method for locating modes of likelihood functions, useful in a variety of incomplete-data problems. On each iteration of the EM algorithm, there are two steps—called the expectation step or the E-step and the maximization step or the M-step. In the E-step, we compute the expected value from the model using current parameters. In the M-step, we compute the maximum likelihood estimation of the parameters from the given data and the model, and set the resulting parameters as the current parameters for the E-step. The objective of the use of EM algorithm is to estimate the vector parameters \( \Theta = [\theta_1; \ldots; \theta_M] \) of M overlapped signals from the observed signal \( y(t) \) received by the transducer.

The direct least squares (LS) approach to this problem requires minimization of the term \( \sum_{m}^{M} s(\theta_m) \) with respect to parameter vectors.

However, E-step and M-step are computed in parallel in EM algorithm, that is, we get all the required current parameters \( \Theta^{(k)} \) and the estimated data \( \hat{x}^{(k)} \) in the E-step; then we use them to calculate the \( \Theta^{(k+1)} \) in the M-step. One alternative to this parallel method is to update the \( \Theta^{(k+1)} \) in the M-step right after estimating \( \hat{x}^{(k)} \) in the E-step, without waiting for the other parameter vector to be estimated. This method is known as the space alternating generalized EM (SAGE) algorithm. The parameter estimation of \( M \) overlapped Gaussian echoes is addressed using the SAGE algorithm. By using this algorithm \( M \) overlapped echoes estimation is translated into \( M \) separated echoes estimation.

The algorithm of parameters estimation of echoes by SAGE algorithm is summarized in algorithm 1.

**Algorithm 1:** A summary of echoes estimation by the SAGE algorithm.

- **Step1.** Start with model order \( M = 1 \).
- **Step2.** Make initial guesses for the parameter vectors \( \Theta = [\theta_1, \theta_2, \ldots, \theta_M] \), tolerance (Tol).
- **Step3.** E-step: compute the expected echoes \( \hat{x}^{(k)} = s(\hat{\theta}^{(k)}), \quad \frac{1}{M} \sum_{m=1}^{M} s(\hat{\theta}^{(k)}) \)
- **Step4.** M-step: iterate the \( m \) parameter vector using the Gaussian-Newton algorithm
  \[ \hat{\theta}^{(k+1)} = \hat{\theta}^{(k)} + \left[H' \left( \hat{\theta}^{(k)} \right) H(\hat{\theta}^{(k)}) \right]^{-1} H' \left( \hat{\theta}^{(k)} \right) \left( \hat{x}^{(k)} - s(\hat{\theta}^{(k)}) \right) \]

- **Step5.** Set \( m = m + 1 \), and then go to Step 3 unless \( m > M \).
- **Step6.** Check convergence criterion:
  - If \( ||\Theta^{(k+1)} - \Theta^{(k)}|| < \text{Tol} \) then go to Step 8.
- **Step7.** Set \( m = 1, k = k + 1 \), and go to Step 3.
- **Step8.** Compute MDL(M) and compare it with the MDL (M=1).
- **Step9.** If MDL decreases or \( M = 1 \), set \( M = M + 1 \), go to Step 2.
- **Step10.** The optimal model order is \( M \), the estimated parameters are \( \hat{\theta}_1; \ldots; \hat{\theta}_M \).

In this study, \( M = 1 \), and the Gaussian modulated cosine pulse is used as model of received signals, it given by:

\[
s(t; \theta) = \beta \cdot \cos(2\pi f_s (t - r) + \phi) \cdot \exp \left( \frac{-(t-r)^2}{\alpha} \right)
\]

where \( \theta = [\beta f_s \phi \alpha] \) is the parameter vector, \( \beta \) is the amplitude of the signal envelope, \( f_s \) is the centre frequency, \( r \) is the arrival time of the wave packet group velocity, \( \phi \) is the phase shift and \( \alpha \) is the width of the received signal. These parameters have intuitive meanings for an ideal surface reflector in a homogeneous propagation path.

III. EXPERIMENTAL SET-UP

To demonstrate the feasibility of the model, the complete measurement system used is shown on Fig. 2. It is composed of an ultrasonic generator impulses carrying the reference (Parametrics 5077PR), an immersion transducer with central frequency 2.5 MHz (Parametrics V306SU), a digital oscilloscope (Techtronic’s TDS 1002), a portable computer with the Wave-Star software which will allow us the acquisition of the data and posting the curves referring to the echoes.

![Schematic diagram of the system measurement](image)

**Figure 2:** Schematic diagram of the system measurement

IV. EXPERIMENTAL RESULTS

We present in this paragraph experimental and estimated waves. Figure 3 and figure 4 shows the received longitudinal and transversal waves before and after loading of the specimen under test.

![Received longitudinal waves before and after bending force](image)

**Figure 3:** Received longitudinal waves before and after bending force
Figure 4: Received transversal waves before and after bending force
The initial vector parameters used to start the estimation algorithm is \( \theta = [1 \ 0.9 \times 10^6 \ 5 \times 10^{-5} \ 0.3 \ 0.6 \times 10^{12}] \). The estimated waves of longitudinal and transversal are shown in Fig.5 and Fig.6, respectively.

Figure 5: Estimated longitudinal waves before and after bending force

Figure 6: Estimated transversal waves before and after bending force

Figure 7 shows the variation of longitudinal and transversal amplitude-waves versus load pending from 0 KN to 40 KN.

Figure 7: Amplitude variation versus load pending
a) longitudinal wave and b) transversal wave

As shown in this figure, the amplitude of longitudinal wave increase with increasing of load pending, while the transversal ones decrease.

Figure 8 shows the variation of central frequency versus the load bending. With increasing the bending force, the central frequency increase for longitudinal waves and decrease for transversal waves.

Figure 7: Central frequency variation versus load pending
a) longitudinal wave and b) transversal wave

Figure 8: Shift time variation versus load pending
a) longitudinal wave and b) transversal wave

V. CONCLUSION

In this study, the longitudinal and transversal waves in material under bending are measured using the Prism technique. The expectation maximization algorithm is used for filtering and parameters estimation of the received signals. Estimated amplitude, central frequency and time of flight of waves are used to verify the effect of bending force on these waves. As expected from previous works the most sensitive
waves to the stress are the pressure mode in loading direction and the shear mode polarized in the loading direction. It would be interesting to model the behavior of waves from a pressurized sample uniaxial depending on the strain.

References

