CORRECTION OF SPECIMEN PARALLELISM DEFECTS FOR ACCURATE SOUND VELOCITY DETERMINATION OF SOFT MATERIALS.

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Abstract

The characterization of soft materials is facing the challenge of poorly controlled shapes and dimensions.

In the method proposed here, the spatial information required for the sound velocity determination is obtained from a controlled displacement of the specimen along the acoustic beam (Z-scan) in the through-transmission configuration. The time-of-flights of the echoes induced by partial reflection of the acoustic burst at the specimen/transducer surfaces are related to the sound velocity through a set of geometrical parameters, including the specimen thickness and faces orientations. The specimen position is accurately determined through an acoustic interferometer. A minimization algorithm establishes the best match between the expressions of time-of-flight based on the geometrical parameters and sound velocity and the experimental echoes time-of-flights.

Allowing for the specimen parallelism defects and by not requiring the specimen thickness to be determined, the Z-scan method has a clear potential in soft material NDE/NDT and specifically in soft biological tissue characterization.

1.INTRODUCTION

Ultrasound velocity is closely related to the material elastic properties. For its determination by time-of-flight measurement, a set of laboratory techniques is available for perfectly parallel specimens the thickness of which has to be accurately determined by other means [1]. Clearly enough, these techniques are not reliable when soft, non parallel specimens are considered

The proposed technique determines the sound velocity in presence of specimen parallelism defects without requiring the thickness determination.

2.METHOD DEVELOPMENT

2.1. The through transmission configuration and the intermediate echoes.

The through-transmission configuration adopted in this work consists in locating the specimen between a pair of facing coaxial transducers of similar characteristics [2], here denominated *excitation* (**E**) and *reception* (**R**) transducers (Figure 1). The whole system is immersed in a thermalized water tank for accurate temperature control (+/-0.01ºC).

The transducer spacing is significantly larger than the specimen, so that no contact occurs between the specimen and the transducers

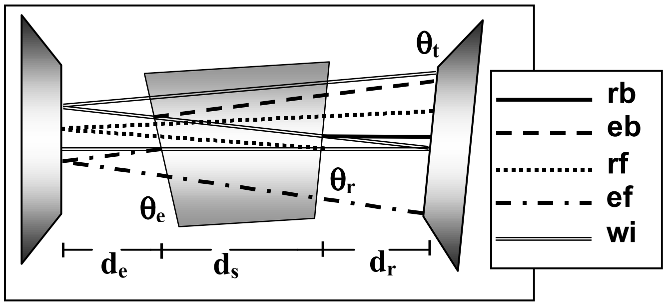

Figure 1 Through-transmission general configuration. Both transducers and specimen are represented along with the acoustic echoes and geometrical parameters

As the transducers, medium and specimen have slightly different impedances, each interface produces a partial reflection of the acoustic burst, yielding a specific low amplitude echo. In this work, echoes that undergo one partial reflection only at a specimen surface will be considered (1st reflection order) (Figure 1).

All echoes produced by the acoustic burst reflection on the transducers only (***Main echoes***) and at the specimen and transducer (***Intermediate echoes***) are detected at the reception transducer (Figure 2) and their time-of-flights determined. Each surface generates two intermediate echoes, one by reflection of the acoustic burst traveling in the forward direction (excitation to reception transducer) and one, while traveling in the backward direction after reflection on the reception transducer.

In this work, the echo time-of-flights will be referred to as following: $\mathbf{T_{Ri}}$ and $\mathbf{T_{wi}}$ (i=1,2) are the time-of-flight of the main transducers echoes determined in absence of the specimen (reference trace) and with the specimen located across the acoustic field respectively. $\mathbf{T_{ij}}$ are the intermediate echoes from the specimen, where "i" (= e, r) is for naming the specimen surface according to which transducer it is facing to, and "j" (= f, b) stands for the direction, forward or backward, the burst is traveling while suffering the specimen reflection.

2.2. Parallel vs. non-parallel configuration

The time-of-flights of the acoustical burst in the through-transmission configuration can be written as the sum of the total transit time in the water and in the specimen:

$$T_{ij} = \frac{d_e^{ij} + d_r^{ij}}{C_m} + \frac{d_s^{ij}}{C_S} \quad (1)$$

$\mathbf{C_m}$, $\mathbf{C_s}$ are the sound velocities in the medium and the specimen, $\mathbf{d_e}$, $\mathbf{d_r}$ the distances between the excitation and reception transducers and the specimen surfaces (water gap) and $\mathbf{d_s}$ the specimen thickness along the acoustic beam.

In the case of a parallel specimen, the distances $\mathbf{d_i}$ are constants for all echoes and the sound velocity in the specimen can be written in function of the time-of-flights [3]:

$$C_S = C_m \left(1 + \frac{\Delta T_{12}}{\Delta T_S} \right) \quad (2)$$

with

$$\Delta T_S = (T_{rf} - T_{ef}) - (T_{eb} - T_{rb})$$

$$\Delta T_{12} = (T_{R2} - T_{W2}) - (T_{R1} - T_{W1})$$

In case of a non-parallel specimen, in addition of the shape, the distances $\mathbf{d_i}$ above depend on the specimen position **Z** that has to be included in the calculation of the specific time-of-flight.

In order to consider the geometry of the specimen and a possible mis-orientation of the receiving transducer, a set of six parameters is defined (Figure 1): 3 distances ($\mathbf{d_e}$, $\mathbf{d_r}$ and $\mathbf{d_s}$) and 3 angles, $\boldsymbol{\theta_e}$, $\boldsymbol{\theta_r}$, the orientation of the specimen surfaces and $\boldsymbol{\theta_t}$ a possible reception transducer angle relatively to the excitation transducer. For simplicity, one writes the transducer spacing $\mathbf{D_t = d_e + d_r + d_s}$.

Here, the sound velocity in the medium (water) is assumed to be known [4].

Taking into account the above definitions, the time-of-flight of each echo can be computed as a function of θ_t , θ_e, θ_r, d_e, d_r, d_s, C_m, C_s.[5]

2.3. Determination of the specimen geometry and sound velocity: the Z-scan

In a first measurement, two reference echoes $\mathbf{T_{R1}}$ and $\mathbf{T_{R2}}$ are recorded without specimen to determine the transducer orientation. The specimen spacing $\mathbf{D_t}$ can be directly estimated from the first $\mathbf{T_{R1}}$ echo:

$$D_t = T_{R1} C_m . \quad \mathbf{(3)}$$

The transducer angle can be extracted from the second main echo (T_{R2}):

$$\theta_t = \pm \frac{1}{2} \cos^{-1}\left(\frac{T_{R2}}{T_{R2} - T_{R1}} - \frac{1}{2} \right). \quad \mathbf{(4)}$$

Then, to determine both specimen sound velocity $\mathbf{C_s}$ and thickness $\mathbf{d_s}$, the proposed method takes benefit of the linear variation between the main and intermediate echoe's time-of-flights and the position **Z** of the specimen along the acoustic beam:

$$\mathbf{T_{ij} = A_{ij}\, Z + B_{ij}} . \quad \mathbf{(5)}$$

In this goal, a scan of the specimen, or **Z-scan**, is performed (Figure 2).

For a perfectly parallel specimen, the slopes $\mathbf{A_{ij}}$ of the intermediate echoes depend only on the medium sound velocity $\mathbf{C_m}$, so: $\alpha_{ij} \equiv 1$. In the general case of non-parallel specimens, the slopes $\mathbf{A_{ij}}$ are affected as well by the specimen sound velocity and surface orientations and have to be written as [5]:

$$A_{ij} = \frac{2}{C_m} \alpha_{ij}(\theta_e, \theta_r, \theta_t, C_s, C_m) \quad \mathbf{(6)}$$

excepted for $\mathbf{T_{W1}}$ that is not altered by the specimen position ($\mathbf{A_{W1} = 0}$).

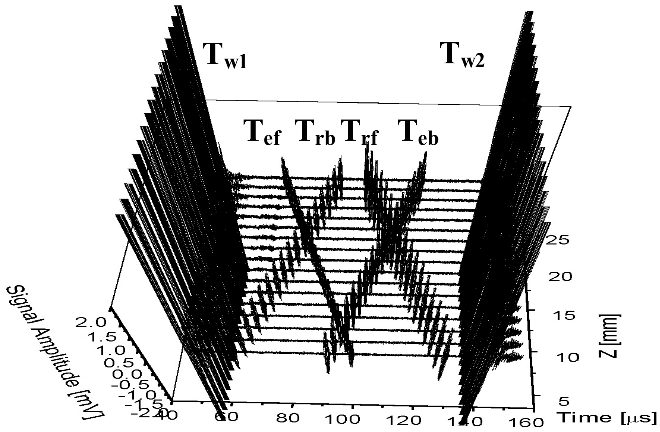

Figure 2 Z-scan. Trace's evolution in function of the specimen position Z (main echoes T_{w1} and T_{w2} are truncated).

Similarly, the intercepts $\mathbf{B_{ij}}$ account for the specimen thickness $\mathbf{d_s}$ and distances to the transducers $\mathbf{D_t}$.

By determining experimentally the Z-scan coefficients $\mathbf{A_{ij}}$ and $\mathbf{B_{ij}}$, the others parameters, among them $\mathbf{C_s}$ and $\mathbf{d_s}$, can be obtained. As the system solution needs to account for experimental uncertainties in the Z-scan coefficients, it must be solved numerically by minimizing the deviation function $\boldsymbol{\sigma^2}$ of the estimated vs. experimental $\mathbf{A_{ij}}$ and $\mathbf{B_{ij}}$, coefficients:

$$\sigma^2 = \sqrt{\sum_{ij}\left(A_{ij,est} - A_{ij,exp}\right)^2 + \sum_{ij}\left(B_{ij,est} - B_{ij,exp}\right)^2} . \quad \mathbf{(7)}$$

3.ILLUSTRATION

3.1. Specimen

A typical soft tissue phantom is made by adding 6 wt% of gelatin (Type B / 225 Blum, Sigma) to distilled water with sodium azide (Riedel de Haën, Seelze, Germany) at 0.02% as a fungus inhibitor.

Gelatin is molded in a PVC tube (30 mm in diameter x 30 mm high) on top of a glass plate that is removed afterward, exposing two opposing free surfaces.

3.2. Experimental Setup

The excitation chain is composed of a signal generator (Wavetek, Model 80) in Sine Burst mode attached to a power amplifier (ENI, 325LA) that feeds the burst signal to an excitation broadband transducer (Panametrics). The acquisition chain is composed of a similar broadband transducer. The signal is directly input into a DSO oscilloscope (LeCroy, LT344) before to be transferred to a PC computer for processing.

The excitation frequency is chosen below the transducer resonance frequency, taking benefit of a higher reflectivity of the transducer at that frequency. This procedure significantly enhances the echo's amplitude and reduces their distortions.

The time-of-flight measurement of the intermediate peaks is determined through the construction of the cross-correlation envelope using the Hilbert transform [3].

A critical step of the method consists in measuring accurately the position of the specimen along the acoustic beam. Therefore, an **acoustic interferometer** has been implemented, using an immersion transducer connected to a network analyzer (Agilent, 4395A) facing a mirror attached to the specimen holder. The specimen position **Z** is obtained from the continuous wave resonance peak separation $\Delta\nu$ by:

$$Z = C_m / 2\Delta\nu \qquad (8)$$

The gelatin specimen is inserted between the two transducers and temperature let to stabilize (20° C). The specimen is oriented so that the intermediate paired echoes appear with similar amplitudes on the oscilloscope trace. The signal trace is digitized at 500MS/s and the interferometer spectrum are acquired simultaneously with 1000x and 100x averaging respectively. The output of the network analyzer (figure 3) is then back-transformed to the spatial domain through the known sound velocity in the surrounding medium [4].

The Z-scan is performed with a total travel of 25 mm and is shown on figure 2. After the Z-scan is completed, the specimen is removed and a reference trace acquired.

All traces, including the reference traces, are processed considering the first main $\mathbf{T_{w1}}$ echo of one of the Z-scan trace acquired at full scale as the reference signal for the cross-correlation-Hilbert transform process. This guaranties an absolute time scale reference. The time-of-flights, determined from the cross-correlation envelope maximum through a peak detection routine, are obtained with a resolution of 1 ns. A linear regression performed on the time-of-flight vs. position plot (figure 2) yields the $\mathbf{A_{ij}}$ and $\mathbf{B_{ij}}$ Z-scan coefficients. The experimental Z-scan coefficients are then input in the minimization routine that yields the geometric parameters and specimen sound velocity that best match the experimental data.

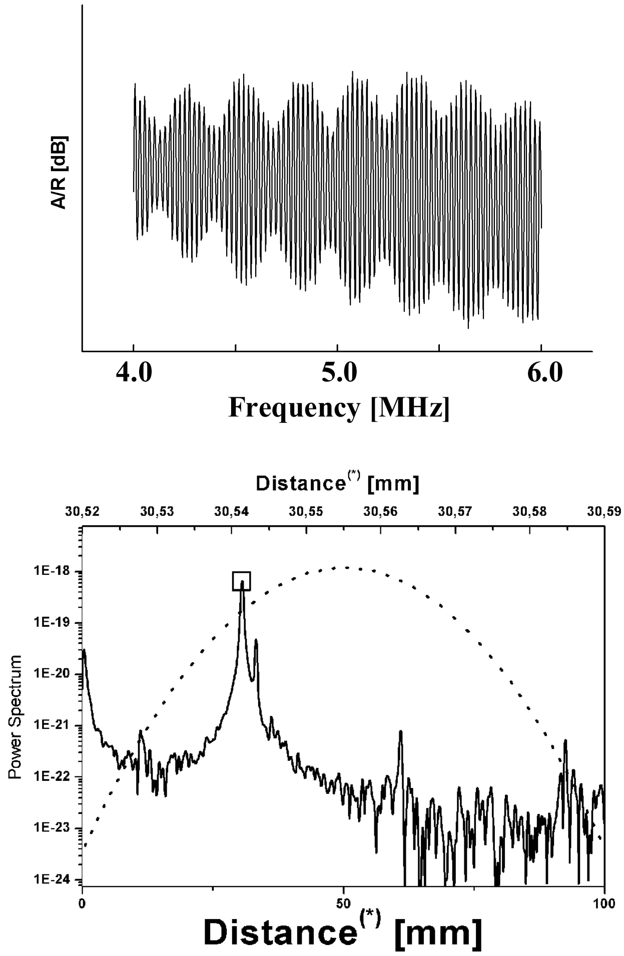

Figure 3 Continuous wave spectrum of the acoustic interferometer above and its back-transform to space domain below (dashed line shows the top of the FFT main peak)

Clearly enough, the success of the method requires both time and space variables to be accurately determined. If the specimen position can be reliably determined with an accuracy of one micron through the acoustic interferometer, the determination of the time-of-flight is subject to distortion due to specimen surface defects.

To analyze the effect of the parameters on the method output, a numerical approach has been implemented. A set of geometrical parameters is first defined. Then the Z-scan coefficients are computed and a random error added. The amplitude of the added random term allows testing the precision of experimental data.

Table 1 presents a set of test data, the Z-scan coefficients that are deduced and the output of the minimization routine. The added error term for Z-scan coefficients was in this case 0.3×10^{-6} for all Z-scan coefficients. Sound velocity in water is taken to be 1480 m/s for a transducer spacing of 0.07 m. One of the deviation function minimum projections, here against $\mathbf{C_s}$ and $\mathbf{d_s}$, is shown on figure 4.

Table 1 Numerical simulation. A_{ij} terms are given in µs/m and B_{ij} terms in µs.

Input param		*Z-scan Coeff.*		*Minimiz output*	
Θ_{e0}	*1.5°*	A_{rb}	*1349.04*	Θ_{e0}	*1.512°*
Θ_{e0}	*-1.5°*	A_{eb}	*1350.09*	Θ_{e0}	*-1.502°*
C_{S0}	*1520m/s*	A_{rf}	*-1347.67*	C_{S0}	*1518.21m/s*
d_{s0}	*0.0175*	A_{ef}	*-1349.96*	d_{s0}	*0.017553*
d_{e0}	*0.045*	A_{W2}	*0.1295*	d_{e0}	*0.044956*
		B_{rb}	*23.1511*		
		B_{eb}	*45.5941*		
		B_{rf}	*75.7234*		
		B_{ef}	*53.2716*		
		B_{W1}	*2.5274*		
		B_{W2}	*95.7556*		

It is interesting to note that the $\mathbf{A_{ij}}$ coefficient, not considering specimen parallelism flaw, should have been identical (1351.35 µs/m), directly related to the sound velocity in water (1480 m/s [4]). It appears from this analysis that, for the precision considered, around 10^{-4} in relative value, the accuracy on the specimen angles is 10^{-2}, and 10^{-3} on the sound velocity.

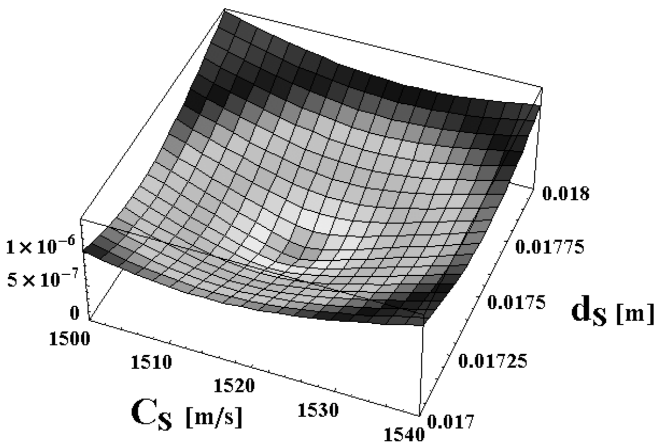

Figure 4 Deviation function σ^2 projected against $[d_S, C_s]$.

It can be considered that the acoustic interferometer as well as the time-of-flight processing routine matches this requisites. The strongest experimental limitation is clearly related to the echo distortion. Working with burst frequency below the transducer resonance has been shown to significantly improve the specimen echo amplitude and reduce their distortions [3].

4.Conclusion

The Z-scan method proposed in this work gives an original approach for determining the sound velocity in specimen not presenting high parallelism and for which the thickness cannot be accurately determined. The specimen thickness is not required to determine the sound velocity but can be deduced simultaneously with the specimen sound velocity and at the very same location of the acoustic beam. It should be appropriate for soft materials and specifically such as soft tissue fragments or biomimetic materials.

The time-of-flight resolution of the order of magnitude of 1 to 0.1 ns and specimen displacement resolution lower that 1 µm would allow providing a sound velocity accuracy close from 10^{-4} on soft materials.

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