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A Wavelet-Based Processing method for simultaneously determining ultrasonic velocity and material thickness

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ABSTRACT

Methods of measuring ultrasonic wave velocity in an elastic sample require data on the thickness of the sample and/or the distances between the transducers and the sample. The uncertainty of the ultrasonic wave velocity measurements generally depends on that of the data available. Conversely, to determine the thickness of a material, it is necessary to have a *priori* information about the wave velocity. This problem is particularly hard to solve when measuring the parameters of biological specimens such as bones having a greater acoustical impedance contrast (typically 3–5 MRayl) than that of the surrounding soft tissues (typically 1.5 MRayl). Measurements of this kind cannot easily be performed. But obtaining the thickness of a bone structure and/or the ultrasonic wave velocity is a important problem, for example, in biomechanical field for the calculation of elastic modulus, or in acoustical imaging field to parameterize the images, and to reference the grey or color level set to a physical parameter.

The aim of the present study was to develop a method of simultaneously and independently determining the velocity of an ultrasonic wave in an elastic sample and the wave path across the thickness of this sample, using only one acquisition in pure transmission mode. The new method, which we have called the "Wavelet-Based Processing" method, is based on the wavelet decomposition of the signals and on a suitable transmitted incident wave correlated with the experimental device, and the mathematical properties such as orthonormality, of which lend themselves well to the time-scale approach. By following an adapted algorithm, ultrasonic wave velocities in parallelepipedic plates of elastic manufactured material and the apparent thicknesses were both measured using a water tank, a mechanical device and a matched pair of 1 MHz ultrasonic focused transducers having a diameter of 3 mm, a focal length of 150 mm and beam width of 2×2 mm at the focus (mean temperature 22°). The results were compared with those obtained with a conventional Pulse-mode method and with the control values, to check their validity. Measurements performed on bovine and human dry cortical bone samples are also presented to assess the limitations of the method when it is applied to elastic biological samples, including those of an equal-wavelength size (≈1.5 mm). The thicknesses and the ultrasonic wave velocities were then measured in this kind of (quasi-) parallelepipedic elastic materials with an mean estimated error ranged from 1% to 3.5% compared to the referenced values.

1. Introduction

The velocity of ultrasonic waves propagating in a solid elastic material is an important property that can be used, for example, in non-destructive evaluation to calculate the stiffness rigidity matrix, or in the biomedical field to parametrize reconstructed images (in ultrasonic tomography [1]). Conventional techniques used for making velocity measurements in materials require information about the thickness of the material under investigation. These thickness measurements are usually calculated from time-of-flight measurements. Depending on the experimental equipment used, this can involve complicated procedures (several data statements, several acquisition mode, several transducers, etc.), which impose fundamental efficiency limitations (error higher than 5%, reproducibility, etc.) on the velocity measurements. In the case of in vitro ultrasound methods of characterizing bone structures for relevant works in biomechanical field (evaluation of elastic modulus for example) or acoustical field (quantitative ultrasonic imaging for example), the occurrence of physical processes associated with the wave propagation generates complex acoustic signals (weak Signal-to-Noise Ratio (SNR), multiple echoes, dispersion, etc.), which it is often difficult to analyze and to interpret in terms of wave paths or depth-dependencies. The main problem arising here

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is that it is very difficult to obtain samples with a regular thickness and parallel faces. A large proportion of the incident ultrasonic energy is also scattered (or simply reflected) and the transmitted proportion is refracted (deviated) after undergoing modal conversion at the water/sample interface. To overcome these problems, the use of low ultrasonic frequencies (<3 MHz) provides an effective alternative approach because some of the zones turn out to be more homogeneous, and the quantity of energy lost during the propagation of the wave therefore decreases. But even with low frequencies, to be able to determine the time-of-flight and thickness, it is necessary to find new methods of recording and processing these signals, and to develop more efficient algorithms.

Several approaches have been used so far for this purpose, such as filtering and spectral analysis methods and a method involving deconvolution based on the use of a transfer function characteristic of the experimental device [1]. Deconvolution algorithms improve the quality of the information in the low ($\rightarrow 0$) and high ($\rightarrow \infty$) frequency ranges, but tend to be over-sophisticated and unstable. Indeed, they are a class of inverse problems associated with regularization process and ill-conditioned systems, and the main drawbacks of the most efficient algorithms are their computational time consuming because they involve often inversion of huge, full or complex matrix, which may not be compatible with an automatic process involving a large number of data. Although there exist optimized [2], faster [3,4], and adaptive [5] methods, deconvolution algorithms are sensitive to artifacts, noise and the bias affecting the repeatability of the measurements. Alternative methods based on multi-scale decomposition procedures, such as those based on wavelet transformation of the signals [6], make it possible to process all the local information and much more of the overall information available in terms of the frequency and time parameters. Instead of performing regularization in order to reduce the effects of inverse filter singularities and to restore the original signal, a wavelet transform can be performed in the deconvolution procedure by regularizing the inverse problem [7,8]. Although this method is highly efficient, it involves performing delicate processing steps and having prior knowledge of the singularities of the signal. When used alone, the wavelet transform method lends itself very well to detecting and discriminating between signals during the data pre-processing phase and to extracting information such as the instantaneous frequency and the evanescent properties of the medium [9] to remove the tiny echoes embedded in a strong noise background [10] and to abolish speckle noise [11]. Another efficient wavelet method is also used to assess the spatial changes occurring in a multi-scale structure [12] and to determine the thickness of irregular plates and granular interfaces [13] from the reflected acoustical waves. The main advantage here is the possibility of performing the optimized shaping of the signal associated with the incident wave propagating through the media [14] and applying a matching process, using the wavelet's mathematical properties. At the experimental level, however, the so-called "wavelet response" method is sometimes poorly suited to automatically operating control situations because it requires the use of many probes with different nominal frequencies corresponding to the wavelet scales, and because it focuses entirely on the reflected wave.

Here we present a new method of simultaneously determining the ultrasonic transmitted wave velocity in an elastic material and the associated thickness without any previous knowledge of either parameter. The new algorithm is based on a wavelet decomposition method, which is applied to the acoustical signals, and on a suitable transmitted signal associated with the incident wave, and correlated with the parameters of the experimental device. The "Wavelet-Based Processing" method (WBP method) uses the mathematical properties of these acoustical signals to measure the time-of-flight of the transmitted wave through the sample in a one-shot transmission mode, and then to calculate the thickness and the velocity simultaneously. This method, which does not require the use of any specialized equipment, allows discriminate placement of the sample in the ultrasonic path. The validity of the results obtained was confirmed by measuring the thickness and the wave velocity in rectangular parallelepipedic manufactured plates, the mean thickness of which was closely determined using calipers to within 0.1 mm. The mean control thicknesses and velocities obtained using a more conventional broadband pulse method are also presented, and cases involving thicknesses of the same order as the wavelength (which will be called the "equal-wavelength" case from now on) will be discussed. Lastly, similar experiments and results are presented on bovine and juvenile human bone samples to assess the limitations of the WBP method as a means of biological tissue characterization.

2. Material and methods

The main working hypothesis adopted in this in vitro experimental study was that the sample was comparable to a parallelepipedic rectangle, and that the ultrasonic incident wave vector was perpendicular to the water/sample interface. Under these assumptions, pure compression waves (ultrasonic waves) were therefore transmitted through water and the sample. Any shear waves, and compression-to-shear wave mode conversion in the sample were neglected. The sample was taken to be homogeneous and isotropic. The wave velocities were taken to be constant and independent of the frequency (non-dispersive). Only the propagation processes were taken into account. The ultrasonic wave attenuation resulting from absorption processes was assumed to be weak and the magnitude of the signals decreased by only a few percent during the propagation. Only the time-of-flight (TOF) of the waves was therefore measured.

To have several measurement points on the sample, linear scanning was performed with the transducers over a distance of L mm (16 mm in this study) with a ΔL-mm (1 mm) step on both sides of the sample, using an ultrasonic mechanical scanner. At each measurement, the depth of the wave path versus the mean thickness (e) of the sample in the sounded area (which will be called "the thickness" from now on), and the corresponding ultrasonic wave velocity v_b (which will be called "the velocity" from now on) were calculated using the Wavelet-Based Processing (WBP) method and a conventional ultrasonic pulse-mode (Pulse-mode) method as the control method. The thicknesses were also compared with those measured using a caliper. With both methods, a digitized initial signal was obtained without any target in order to measure the TOF t_0 (μs) and the velocity v_0 (m s^{-1}) of the ultrasonic wave, given the distance (d) between the transmitter and the receiver. The data obtained in the first experiment were subsequently used to determine the linear mechanical variations occurring in the ultrasonic mechanical scanner due to the mechanical offset effects.

2.1. Ultrasonic mechanical scanner

Measurements were performed on the ultrasonic mechanical scanner developed at the Laboratory of Mechanics and Acoustics (LMA). The apparatus used consisted of a main symmetrical arm carrying two secondary transversal arms. Each arm supported an aligned transducer, which could be moved linearly. Increments were multiples of 0.75 hundredths of millimeters. The object to be tested was placed in the presumed geometrical center of the bench so that the maximum distance between the transducers and the center was 150 mm. The surrounding fluid medium was water at a temperature of (Θ) (degrees). The matched pair of transducers used for data acquisition purposes were piezo-composite