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Accuracy of coded excitation methods for measuring the time of flight: Application to ultrasonic characterization of wood samples

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ABSTRACT

Ultrasound computed tomography (USCT) using the transmission mode is a way to detect and assess the extent of decay in wood structures. The resolution of the ultrasonic image is closely related to the different anatomical features of wood. The complexity of the wave propagation process generates complex signals consisting of several wave packets with different signatures. Wave paths, depth dependencies, wave velocities or attenuations are often difficult to interpret. For this kind of assessment, the focus is generally on signal pre-processing. Several approaches have been used so far including filtering, spectrum analysis and a method involving deconvolution using a characteristic transfer function of the experimental device. However, all these approaches may be too sophisticated and/or unstable. The alternative methods proposed in this work are based on coded excitation, which makes it possible to process both local and general information available such as frequency and time parameters. Coded excitation is based on the filtering of the transmitted signal using a suitable electric input signal.

The aim of the present study was to compare two coded-excitation methods, a chirp- and a wavelet-coded excitation method, to determine the time of flight of the ultrasonic wave, and to investigate the feasibility, the robustness and the precision of the measurement of geometrical and acoustical properties in laboratory conditions. To obtain control experimental data, the two methods were compared with the conventional ultrasonic pulse method.

Experiments were conducted on a polyurethane resin sample and two samples of different wood species using two 500 kHz-transducers. The relative errors in the measurement of thickness compared with the results of caliper measurements ranged from 0.13% minimum for the wavelet-coded excitation method to 2.3% maximum for the chirp-coded excitation method. For the relative errors in the measurement of ultrasonic wave velocity, the coded excitation methods showed differences ranging from 0.24% minimum for the wavelet-coded excitation method to 2.62% maximum for the chirp-coded excitation method. Methods based on coded excitation algorithms thus enable accurate measurements of thickness and ultrasonic wave velocity in samples of wood species.

Keywords: Ultrasonic measurement; coded-excitation method; chirp waveform; wavelet function; wood specimens

INTRODUCTION

Ultrasound computed tomography (USCT) in the transmission mode is way to detect and assess the dimensions of decay in trees and in wood structures [1]–[3]. The propagation of ultrasonic waves through a tree trunk generates very complex signals, formed of several packets with different acoustical signatures. One possible solution is optimal smoothing of propagation and diffraction effects using low frequencies (≤ 500 kHz). However, the resolution of the signal and of the reconstructed image is bound to decrease. Even with low frequencies, the wave propagation and diffraction processes generate complex acoustic signals consisting of several packets with different signatures, whose dependency, reflectivity, wave velocity or attenuation are often difficult to analyze and interpret. The quality of the contrast-to-noise ratio, the dynamics and resolution of the ultrasonic image depend on our ability to separate the wave packets, whose properties (phases and amplitudes) can be analyzed using signal processing before the image is reconstructed [4]. Several approaches have already been proposed to solve this problem including filtering, spectrum analysis, and a deconvolution-based method based on a characteristic transfer function of the experimental device. The main drawback of the most precise algorithms is the heavy computational cost, which makes them incompatible with automatic processing of a large number of data [5]. Even if optimized, faster, or adaptive methods were available, the algorithms could be sensitive to noise effects and to repeated measurement bias.

Techniques for transmitting encoded waveforms, such as the chirp-code excitation method, are potential alternatives of great interest in the field of acoustical imaging, and in particular for medical ultrasounds [6]–[9]. Used for the examination of living trees, the technique would allow a higher energy field to be transmitted, thus improving the penetration of the wave [10]. However, prolonging the signal reduces the resolution of the determination of the arrival times and the detection of the different interfaces. Depending on the wavelength, this causes an overlap between the wave packets that results in a significant loss of information. Lasaygues *et al.* [11] showed that the duration of the chirp signal had a weak influence on the calculation of physical parameters such as the thickness and the ultrasonic wave velocity.

By encoding a recognizable signature in the transmitted waveform, a matched filter makes it possible to identify the signature and compress the received signal into several localized packets. The method, based on multi-scale decomposition procedures, such as wavelet transformation of the signals, is proposed here as a technique to process available local and general information including time and frequency parameters. The time (axial) resolution of the order of the half wavelength is kept, while the signal-to-noise ratio is improved. When directly used on its own, the wavelet transform method lends itself very well to detecting and discriminating between signals in the data pre-processing phase and extracting information such as the instantaneous frequency and the evanescent properties of the medium [12], or cleaning the speckle noise [13]. The main advantage is the possibility to optimize the shaping of the signal associated with the incident wave propagating through the medium, and applying a matching process with the wavelet mathematical properties. Our algorithm is based on the wavelet decomposition of the received signal, and on a suitable transmitted signal correlated with the parameters of the experimental device. Exploiting the mathematical properties of these acoustical signals, the wavelet-code excitation method is used to measure the time of flight of the wave transmitted through the sample with just one transmitted signal, and then to simultaneously calculate the thickness of the sample and the ultrasonic wave velocity within the sample [14]. This article explores the ability of coded-excitation methods using chirp or wavelet waveforms to improve the measurement of these parameters in the case of wood specimens. The thickness and ultrasonic wave velocity measurement is a function of the signal-to-noise ratio (SNR), and of the procedure used to extract the time of flight (TOF) from the recovered waveform, which, in wood, depends on the coherent noise of the material itself. It is thus necessary to progress in separate and successive steps, to independently discuss all of these effects in an experimentally controlled environment. Even if the coded excitation methods are a way to improve the SNR at the receiver, the study of the effect of noise is not included in the parameters to be controlled here. In previous studies, we analyzed some noise effects on experimental and numerical data [5], [15], [16]. The objective of this academic study is to compare the two methods on calibrated and clean wood samples, before testing uncalibrated natural medium and wooden logs. The experiments were carried out in transmission mode using 500 kHz-plane transducers. Two parallelepiped-shaped samples of two wood species (Tatajuba, *Bagassa guianensis* and Iroko, *Milicia excelsa*), and a calibrated polyurethane resin sample as reference, were tested. The methods and results obtained were compared with those obtained with a more conventional pulse method, based on a protocol requiring three measurements for the calculation of the parameters.

METHODS AND MATERIAL

Ultrasonic measurements

The sample was a parallelepiped rectangle. The ultrasonic incident wave beam was perpendicular to the water/sample interface. The ultrasonic wave was therefore transmitted through the sample and reflected off the back wall. In this study, only pure compression waves were taken into account. No shear waves were propagated in the sample under normal incident conditions. The wave velocities were assumed to be constant and independent of the frequency (non-dispersive material). Only the propagation processes were taken into account. The ultrasonic wave attenuation due to absorption processes was assumed to be weak, and the magnitude of the signals decreased by only a few percent during propagation. The diffraction effects due to the ultrasonic wave beam (in the sense of O'Donnell *et al.* [17]) were assumed to be weak, and to have no effect. Therefore, only the duration of the ultrasonic wave propagation, hereafter "time of flight" (TOF) of the ultrasonic wave, was considered and measured.

The experiment was conducted in transmission mode using two transducers facing each other with their axes aligned (Fig. 1). The transducers were moved linearly over a distance of 80 mm and were positioned automatically from the right to the left of the sample at 4 mm intervals (Fig. 2). At each position of the coupled transducers (from 1 to 21), the sample thickness and the ultrasonic wave velocity in the sample were calculated. The center frequency of both transducers (Imasonic®, Voray sur l'Ognon, France) was 500 kHz. The sample was placed at the focal spot (~150 mm from the transducer) parallel to the transducer surface. At the focal spot, the active area (~400 mm^2) of the transducer was smaller than the length and the width of the parallelepiped sample. The total linear displacement (80 mm) of the transducers is greater - and the pitch between two positions (4 mm) lower - than the beam width (~20 mm). This choice makes it possible to calculate mean values and standard deviations for several significant points per sample.

A waveform generator and preamplifier (TTI® TGA1241, Thurlby Thandar Instruments, UK) was used to produce the arbitrary waveform. The stored signals (Agilent® DSO5014A, Keysight, USA) were used to determine the TOF. The signal processing algorithms were implemented on a personal computer.

The electro-acoustical device and the transducers therefore served as a continuous linear stationary causal filter, and so the input $x(\mathrm{t})$ and output $u(\mathrm{t})$ signals were connected by convolution (noted $\otimes$):

Eq. 1 $u(t) = (x \otimes h_M)(t)$

where $h_M(t)$ is the response of the object, and

Eq. 2 $x(t) = (h_T^* \otimes s)(t)$

where s(t) is the electric input signal conveyed to the transmitter via the waveform generator, and the $h_T^*(t)$ is assumed to be equivalent to the electro-acoustical transfer function.

In transmission mode, and in the absence of a sample and with no propagation distortions, the response $h_M(t)$ in water depends on the time delay of the wave, which is proportional to the distance (d) between the two transducers, and to the reference velocity v_{ref} of ultrasound in water. In the absence of a sample, the reference output signal $[u(t)]^{ref}$ is therefore equal to the input signal x(t), which is invariant by translation:

Eq. 3 $[u(t)]^{ref} = x(t) \otimes \delta\left(t - \frac{d}{v_0}\right) = x\left(t - \frac{d}{v_0}\right) = x(t) = \left(h_T^* \otimes s\right)(t)$

The pulse method

The thicknesses and velocities were calculated using a conventional ultrasonic pulse method to obtain control experimental data. The conventional pulse method is described in Loosvelt et Lasaygues [14]. In this case, the electric input signal s(t) is a pulse function, mathematically modeled as a Dirac distribution δ(t), and the reference output signal can be modeled as a copy of the electro-acoustical transfer function (Fig. 4):

Eq. 4 $[u(t)]^{ref} = \left(h_T^* \otimes s\right)(t) = \left(h_T^* \otimes \delta\right)(t) = h_T^*(t)$

Using a pulse function as the electric input signal s(t) conveyed to the transmitter, measurements were carried out as follows:

- One signal in transmission mode in the absence of a sample to obtain the time t_0 and the reference ultrasonic wave velocity v_{ref};
- Two signals in echo mode on each side of the sample to determine a time t_l (respectively a time t_r) for the reflected wave on the left (respectively on the right) interface of the sample, and calculating the thickness (Fig.2):

Eq. 5 $e = d - \left(\frac{v_{ref}}{2}\right)(t_l + t_r)$

For each measurement, times t_l and t_r were determined by searching for the maxima of the first wave packet corresponding to the first echo.

- One signal in transmission mode in the presence of a sample to obtain the ultrasonic wave velocity:

Eq. 6 $v_e^2 = v_{ref}^2 \left[1 + \left(\frac{\tau\, v_{ref}}{e}\right)\left(\frac{\tau\, v_{ref}}{e} - 2\right)\right]^{-1}$

where τ is a time delay calculated by cross-correlating the initial signal obtained in the absence of a sample $[u(t)]^{ref}$.

The chirp-coded excitation method

In the chirp-coded excitation method, the electric signal s(t) was a pseudo-periodic frequency-modulated function (chirp waveform):

Eq. 7 $s(\mathrm{t}) = \left(1 - cos\left[2\pi\, {}^{t}/_{t_p}\right]\right) sin[2\pi f_1 t + \pi k_0 t^2]$

$k_0 = \frac{f_2 - f_1}{t_p}$ defines the rate of the frequency sweep of the chirp waveform. The duration $\mathrm{t_p}$ of the chirp waveform was 25.55 µs and the chirp frequency was swept between f_l = 0.25 MHz and f_2 = 1 MHz. According the conclusions of our previous work [11], these values enabled a minimum error in the calculation of the physical parameters. The process of coded excitation is based on filtering of the transmitted signal by the replica (inversed) of the electric input signal conveyed to the transmitter (Fig.4):

Eq. 8 $\gamma(t) = u(t) \otimes s(-t) = \left(h_M \otimes h_T^* \otimes s\right)(t) \otimes s(-t) = \left(h_M \otimes h_T^*\right)(t) \otimes R_{ss}(t)$

where $R_{ss}(t)$ is the autocorrelation function of the signal s(t).

Using the chirp waveform as the electric input signal s(t) conveyed to the transmitter, the sample thickness and the ultrasonic wave velocity in the sample were calculated as follows:

Eq. 9 $e = v_{ref}\left[t_0 - \frac{3t_1 - t_2}{2}\right]$

and

Eq. 10 $v_e = v_{ref}\left[\frac{2t_0 - 3t_1 + t_2}{t_2 - t_1}\right]$

where t_0 is the time of the transmitted wave crossing distance (d) in water in the absence of a sample. Time t_1 corresponds to the propagation time of the ultrasonic wave for the distances l_1 and l_2 in the water and the distance (e) in the sample (Fig. 2). Time t_2 corresponds to the propagation time of the ultrasonic wave for the distances l_1 and l_2 in the water and the distance (3e) in the sample.

The measurements were then carried out as follows:

- One signal in transmission mode in the absence of a sample to obtain the time t_0 and the reference ultrasonic wave velocity v_{ref};
- One signal in transmission mode in the presence of sample to obtain the times t_1 and t_2. The first time t_1 was determined by searching for the first maximum of the function $\gamma(\mathrm{t})$, and the second time t_2 was determined on the second maximum of the function corresponding to the back wall echo.

The wavelet-coded excitation method

If the input signal $\mathrm{x}(\mathrm{t})$ is a wavelet denoted $\varphi_\mathrm{J}(\mathrm{t})$ which is centered on the fixed scale J (J ∈ Z) and has properties suitable for a specific wavelet analysis – the properties were previously analyzed by Y. Meyer and S. Jaffard [18], [19] – Eq. 1 can be written:

Eq. 11 $u(\mathrm{t}) = \left(\varphi_\mathrm{J} \otimes h_\mathrm{M}\right)(\mathrm{t})$

The coded-excitation method is then based on a time-scale decomposition of the signal $u(\mathrm{t})$ giving the suitable coefficients $\mathrm{X}_j(\mathrm{t})$:

Eq. 12 $\mathrm{X}_j(\mathrm{t}) = \langle u(\mathrm{t}), \varphi_\mathrm{j}(t)\rangle = h_\mathrm{M}(\mathrm{t}) \otimes \left[\varphi_\mathrm{J} \otimes \varphi_\mathrm{j}\right](\mathrm{t})$

where φ_j is a wavelet centered on the scale j (∀ j ∈ ℤ). The properties of the wavelet decomposition (an orthogonal decomposition in this work) are such that the coefficients $\mathrm{X}_j(\mathrm{t})$ nullify everywhere except for j = J.

Eq. 13 $\mathrm{X}_j(\mathrm{t}) = \mathrm{X}_\mathrm{J}(\mathrm{t}) = h_\mathrm{M}(\mathrm{t}) \otimes \delta(\mathrm{t}) = h_\mathrm{M}(\mathrm{t})$

In transmission mode, the transmitted signal can be modeled as the sum of two wave packets located at times t_1 and t_2. Because the samples have parallel interfaces, acoustical modeling assumes that $h_\mathrm{M}(\mathrm{t})$ is comparable to a sum of Dirac delta functions. The output signal $\mathrm{u}(\mathrm{t})$ can be modeled as follow:

Eq. 14: $\mathrm{u}(\mathrm{t}) = A_1\varphi_\mathrm{J}(t - t_1) + A_2\varphi_\mathrm{J}(t - t_2)$

A_1 and A_2 are the amplitudes of the wave packets located at times t_1 and t_2.

As shown by Loosvelt and Lasaygues [14], the decomposition on a dyadic grid of wavelets with orthogonality properties makes it possible to determine the cross-correlation function (wavelet coefficient $\mathrm{X}_j(\mathrm{t})$) on the fixed J scale, and to locate the TOF of the waves. The result is the sum of functions $X_j(\mathrm{t})$.

Eq. 15: $X_j(\mathrm{t}) = A_1\langle\varphi_\mathrm{J}(t - t_1), \varphi_\mathrm{j}(t)\rangle + A_2\langle\varphi_\mathrm{J}(t - t_2), \varphi_\mathrm{j}(t)\rangle$

Eq. 16: $X_j(\mathrm{t}) = X_j(\mathrm{t} - t_1) + X_j(\mathrm{t} - t_2)$

If it is possible to process the initial signal received such that it is identical to a wavelet function, this method then yields TOF without the involvement of any further filtering effects. The measurements were carried out as follows:

- One signal in transmission mode in the absence of a sample to obtain the time t_0 and the reference ultrasonic wave velocity v_{ref};
- One signal in transmission mode in the presence of sample to obtain the times t_1 and t_2.

The sample thickness and the ultrasonic wave velocity in the sample were calculated using Eq. 9 and Eq. 10.

The wavelet function was the Meyer-Jaffard function (Fig. 3 and Fig. 4). Full details of this function can be found in Loosvelt and Lasaygues [14]. In the present work, the wavelet function was adapted to the frequency of the transducers (500 kHz), and the center frequency was 450 kHz (J = -5) (Fig. 3). The procedure for creating the wavelet function was strictly identical to that presented in Loosvelt and Lasaygues [14]. The input signal x(t) was digitized in the form of wavelets $\mathrm{\varphi_J(t)}$ using the spectral deconvolution of the desired wavelet function by the reference output signal $[\mathrm{u(t)}]^{ref}$ (Eq. 4):

Eq. 17 $\mathrm{s(t)} = \mathrm{\varphi_J(t)} \frac{\otimes}{\otimes} [u(t)]^{ref}$

where $\frac{\otimes}{\otimes}$ denotes the operation of deconvolution.

As shown in Fig. 3, the fit between the experimental and theoretical curves is correct, except around the nominal frequency. The effect on the temporal signal is negligible, and does not influence the resolution of the TOF detection algorithm. At this stage, it is worth noting that the chirp- and the wavelet-coded excitation methods require only one transmitted signal for calculation of the velocity and thickness of the ultrasonic wave, whereas the pulse method requires three signals (1 transmitted and 2 reflected signals). For the pulse method, the calculation of the ultrasonic wave velocity depends on the measurement of thickness, and therefore on measurement error. For the protocol used for the chirp- and wavelet-coded excitation method, the two parameter calculations are independent.

Samples preparation

Experiments were conducted on one polyurethane resin sample (length = 170 mm, width = 110 mm, thickness = 18.34±0.01 mm, density = 1165kg/m^3) and two samples of wood species (length = 130 mm, width = 60 mm): Tatajuba, *Bagassa guianensis* (thickness = 10.27±0.02 mm, density = 800 kg/m^3), and Iroko, *Milicia excelsa* (thickness = 9.55±0.07 mm, density = 640 kg/m^3) (Fig. 5). All the samples were prepared in the form of rectangular parallelepiped-shaped plates by cutting in the radial direction of tree fibers using a scroll saw (Rexon® BS10, Taiwan), and were tested in the ultrasonic experiments at a moisture content above 30%. The reference average thicknesses at five arbitrary points near the middle of the samples were measured using a caliper (Absolute Digimatik Solar®, Mitutoyo, Kanagawa, Japan). Control values for the thicknesses are given in the Table 1.

RESULTS AND DISCUSSION

The water temperature in the tank ranged from 22.9°C to 23.1°C, and the ultrasonic wave velocity in water was v_{ref} = 1486±0.5 m/s. The distance (d) between the transducers was about 50 cm with a reference TOF of 334.15±0.04 µs, whatever the method used (Fig. 4). Note that the thicknesses were 3 to 6.1 times greater than the wavelength of the ultrasonic wave in water (λ = 3 mm). All the signals are normalized and the signal dynamics were not studied in this work. The desired multiple transmitted and reflected signals do not overlap and can be identified from the main signal. Fig. 6 shows the sounded area in mm along the tangential axis. This representation shows the time shift of the signals in the parallel displacements of the two transducers due the mechanical offset of the bench. Since the shape and the amplitude of these signals remained unchanged, the algorithms are applicable to any displacement of the transducers.

For the chirp-coded excitation method, the times t_1 and t_2 were obtained by subtracting the duration of the chirp function (25.55 µs) from the measured times of ultrasonic waves propagating from the transmitter to the receiver in the presence of a sample (e.g. for the resin sample, t_1 = 354.65 µs - 25.55 µs = 329.10 µs; t_2 = 368.75 µs - 25.55 µs = 343.20 µs (Fig. 7)).

For the wavelet-coded excitation method, the times t_1 and t_2 were measured by cross correlating the output signal $u(t)$ with an analyzing wavelet pattern. Fig. 8 shows the result in the case of the resin sample. The time t_1 of the first transmitted signal is equal to that obtained by the chirp-coded excitation method (t_1 = 329.10 µs). The time t_2 of the second signal is equal to 343.60 µs. It is not located exactly at the maximum of the wave packet. The times measured by the wavelet-coded excitation method do not always correspond to maximum energy. The pulse method and chirp-coded excitation method allow to determine the times corresponding to the maximum energy of the wave packets. The result depends on the transmitted energy, and the measured times correspond to maximum energy levels. The wavelet-coded excitation method uses the mathematical properties of the wavelet function and of the orthogonal decomposition, regardless of the transmitted energy.

Table 1 shows mean values and standard deviations of thicknesses and velocities calculated for 21 transducer positions (distance: 80 mm, pitch: 4 mm) for each sample using:

- a caliper for reference thicknesses;
- the pulse method for reference ultrasonic wave velocities;
- the chirp-coded excitation method with the duration of the chirp function of 25.55µs;
- the wavelet-coded excitation method with the wavelet centered on the fixed scale J = -5.

The relative error is given by this formula $\delta x = \frac{\Delta x}{x}$, where the variable x is successively the mean value of the thickness and of the ultrasonic wave velocity.

For the measurement of the thicknesses (Fig. 9), the relative errors comparing the physical and ultrasonic measurements in the case of the pulse method were similar, around 1%. The relative errors for the resin and Iroko samples were higher than those for the Tatajuba sample. Whatever the sample, the thickness measurements using the chirp-coded excitation method involved a significant increase in relative errors compared with the pulse method and wavelet-coded excitation method, ranging from 1.91% (resin) to 2.30% (Iroko). The relative error of the wavelet-coded excitation method was lower than that of the other methods, ranging from 0.33% (resin) to 0.63% (Iroko). The wavelet-coded excitation method was found to be more accurate than the pulse method or the chirp-coded excitation method for the evaluation of sample thickness.

Apart from the uncertainty of the caliper measurements, which was around ±0.01 mm, several reasons linked to the experimental devices and methods used may explain the differences between the physical and ultrasonic measurements. Nevertheless, since the thickness varied little from one part of a sample to another, the estimation of the mean thickness was more precise using a caliper, and was found to differ from the thickness measured at the different positions because the ultrasonic beam, whose size was larger than that of the caliper, was more sensitive to heterogeneities of the medium.

Relative errors in the measurement of ultrasonic wave velocity (Fig. 10), were calculated by comparing the pulse method with the two coded excitation methods. The relative errors were less than 2.6%. For the resin sample, the wavelet-coded excitation method (relative error of 0.24%) was better than the chirp-coded excitation method (relative error of 1.37%). All the methods gave worse ultrasonic wave velocity measurements (the higher relative errors) for the samples of wood species, and better thickness measurements (the lower relative errors), for the Tatajuba sample than for the Iroko sample. The wavelet-coded excitation method produced better results than the chirp-coded excitation method for the samples of wood species than for the resin sample.

Possible reasons for these discrepancies are linked to the properties of the material, the method used or to the experimental configuration. The propagation of the ultrasonic wave was collinear to the radial direction of the tree fibers (Fig. 5). At a frequency of 500 kHz, the wavelength of the propagating wave was around 4 mm in the samples of the two wood species, and larger than the micrometer scale structure.

Density and mechanical properties vary greatly within the annual rings inside the shaft because of the presence of earlywood and latewood. (Fig. 5.C). Due to differences in ring curvatures, the geometric center of the orthotropic reference differs locally within one sample, as well as from one sample to another. This may explain the differences in the parameters, and the standard deviations in the set of measurements. At the wavelength scale, the curvature is smoother for the Iroko sample than for the Tatajuba sample, and its effect on depth propagation is smaller. This may explain why the ultrasonic wave velocity measurement error for the Tatajuba sample was greater than that for the Iroko sample. The difference in the state of the interface from one side of the specimen to the other can also have a significant effect on the penetration of the wave into the sample, and hence on the measurement of thickness or of ultrasonic wave velocity (in particular the uncertainty of the measurement of time t_2).

The position of the ultrasonic beam with respect to the generator parallel to the tangential axis of the samples must be ensured in order to avoid the effects of the ring curvature on beam scattering when the transducers move over a distance of 80 mm. The standard deviations on the measurements can be explained by the heterogeneity of the materials as a function of the measuring zone. The resin sample is homogeneous, and the measurements varied slightly from one position to another, with weak standard deviations. In wood specimens, the standard deviations were higher, which may reflect their heterogeneity. The wavelet-coded excitation method is less sensitive to these phenomena because the standard deviations (for both the thickness and the ultrasonic wave velocity) are lower than those obtained with the other methods.

Samples of wood species are orthotropic whereas the resin sample is assumed to be isotropic. The anisotropy of the sample is extremely important for the estimation of the physical parameters and influences the distribution of the energy of the waves and the quality of the transmitted and reflected signals, whatever the method used.

To summarize, the wavelet-coded excitation method is less sensitive to the heterogeneity and the anisotropy of the medium than the chirp-coded excitation method. The 25.55 µs-chirp wave is slightly resolved in the axial plane of the ultrasonic beam. In Eq. 8, the signal is filtered by the response of the transducer, which may also introduce even a slight distortion. The cross correlation makes it possible to solve the inverse problem of detection of TOF. Conversely, in Eq. 13, the wavelet-coded excitation method allows the signal to be adapted to the electronic system. The recorded signal depends only on the response of the medium. The axial resolution is better and less sensitive to changes in the structure of the medium. The relative error on the final measurements of the parameters is smaller, and the wavelet-coded excitation method could be the best way to improve measurement accuracy.

CONCLUSIONS

Agreement between the thickness and ultrasonic wave velocity measurements may result from two characteristics in the coded excitation method using 500 kHz-transducers. The methodology genuinely provides more accurate estimated TOF and enables better assessment of the geometrical and acoustical parameters. Above all, the coded excitation method was shown to be a more consistent and robust approach to parameter estimation. In this article, three methods were compared. The first was the conventional method using a pulse as the transmitted signal. The two other methods were coded excitation methods based successively on a chirp function and a wavelet function. The wavelet-coded excitation method integrates all the time and the frequency information required to measure physical parameters from a one-shot in transmission-mode acquisition. This method is more precise than the chirp-coded excitation methods discussed in this article. However, this method requires very precise calibration of the measuring setup since the transmitted signal must have precise wavelet mathematical properties. Calibration can be complex for some experimental configurations and can introduce errors in the parameter calculation algorithm. This should be taken into account as a limitation of the wavelet-coded excitation method. Notwithstanding that remark, to continue with this work, the effect of the SNR on the different methods should be measured using a clean sample and simulation of relevant random noise. A thorough study of the attenuation of the waves as a function of the distance from the transducer is also necessary. The methods should also be checked with samples whose surface contains non-rectified imperfections. Indeed, the encoded excitation method works well when the signature of the output signal is not too modified with respect to the input signal (low dispersion). However, ultrasound-material interaction phenomena and the coherent noise of the wood itself can considerably modify the acoustic signatures of the wave packets. Testing wooden logs and standing trees is therefore imperative. The procedure should be tested using contact probes (with gel). The choice of a specific wavelet function, and then the calibration process are fundamental steps in the in-situ application of the method.

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Table 1: Mean values and standard deviations of the thicknesses and velocities calculated for 21 transducer positions (distance: 80 mm, pitch: 4 mm) for each of the rectangular parallelepiped samples using a caliper, the pulse method, the chirp-coded excitation method with the duration of the chirp function of 25.55 µs, and the wavelet-coded excitation-coded excitation method. (*) Relative error: $\delta x = \frac{\Delta x}{x}$.

Fig. 1: Overview of the ultrasonic measurement set-up: mechanical scanner, 500 kHz-transducers (Imasonic®); sample between transmitter and receiver; water tank.

Fig. 2: Signal paths in transmission- and echo-mode measurements to determine the compressional wave velocities and wall thickness of a parallelepiped sample. Top case: the transmission mode for the time-of-flight measurement in the chirp- and the wavelet-coded excitation method. Middle case: the echo and the transmission mode for the time-of-flight measurement in the pulse method. (Vertical arrows) Linear displacement of transducers over ±40 mm. Bottom case: initial signal path in transmission-mode measurements for determining initial ultrasonic wave velocity in the absence of sample.

Fig. 3: Comparison between the theoretical wavelet function and the experimental wavelet function (J = -5) transmitted in the absence of a sample (top) time graphs (bottom) modulus of the Fourier transform.

Fig. 4: Comparison between the electro-acoustical transfer function (500 kHz) using a pulse as the electric input signal (pulse method), the cross-correlation function between transmitted and generated 25.55 µs-chirp waveforms (chirp-coded excitation method), and the experimental wavelet function (J = -5) transmitted in the absence of a sample.

Fig. 5: Rectangular parallelepiped samples of two wood species (A) *Bagassa guianensis* – Tatajuba (thickness = 10.27±0.02 mm, density = 800 kg/m^3); (B) *Milicia excelsa* – Iroko (thickness = 9.55±0.07 mm, density = 640 kg/m^3); (C) Radial plane.

Fig. 6: Time shift of the wavelet input signal due to linear scanning along the tangential axis.

Fig. 7: Cross-correlation $\gamma(\mathrm{t})$ between the transmitted signal through the resin sample and the generated chirp waveform with a duration of 25.55 µs. (Dark circle) Measurement of the T.O.F. t_1 = 354.65 µs - 25.55 µs = 329.10 µs ; t_2 = 368.75 µs - 25.55 µs = 343.20 µs.

Fig. 8: Signal transmitted through the resin sample when the electric input signal is a wavelet waveform (J = -5). (Dark circle) Measurement of the T.O.F. $t_1 = 329.1$ μs, and $t_2 = 343.6$ μs, using the algorithm developed by Loosvelt and Lasaygues [14].

Fig. 9: Relative error (%) of the mean values of the thickness measurements, between the measurement using a caliper (as reference) and measurement using the pulse method, the chirp-coded excitation method with a duration of 25.55 μs, and the wavelet-coded excitation method.

Fig. 10: Relative error (%) of the mean values of the ultrasonic wave velocity measurements between the measurement using the pulse method (as reference method) and the measurement using the chirp-coded excitation method with a duration of 25.55 μs, and the wavelet-coded excitation method.