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# Use of a chirp-coded excitation method in order to improve geometrical and acoustical measurements in wood specimen

Philippe Lasaygues[a]*, Andrés Arciniegas[a,b], Loïc Brancheriau[b]

[a]*Laboratory of Mechanics and Acoustics, UPR CNRS 7051, Aix-Marseille University, Centrale Marseille, 13009 Marseille, France*
[b]*BioWooEB, UR CIRAD 114, TA B-114/16, 73 Rue Jean-François Breton, 34398 Montpellier Cedex 5, France*

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## Abstract

Methods for measuring ultrasonic wave velocity in an elastic material require knowledge of the thickness of the sample. In general, the precision of this knowledge determines the accuracy of the experimental technique for measuring velocity. With the same restriction, measuring thickness of a material require a knowledge of the time-of-flight of the wave propagating. This problem is particularly acute in measuring parameters in wood specimen with an acoustical impedance contrast higher than the surrounding media. The aim of the present study was to compare chirp-coded excitation methods to determine time-of-flight, and to evaluate the precision of the measurement in function of several temporal durations. The apparent thicknesses and ultrasonic wave velocities in parallelepipedic plates of resin and wood material were measured using the method, and using, as reference, a pulse-mode approach. The relative errors of thickness measurement comparing to the results from caliper measurements are 0.1% to 6.81%. For velocity, the chirp-coded excitation method shows differences with reference method, from 0.78% to 3.64%.

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*Keywords:* chirp-coded excitation method ; thickness and velocity measurements ; wood characterization

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## 1. Introduction

The use of ultrasonic waves is one examination possibility of characterization of decays in wood structures [1]. The resolution of the device is closely related to the interferences between the various structural materials. The main fields are the sizing (including the thickness measurement) and the parametrical discrimination (including the wave

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* Corresponding author. Tel.: 33 (0) 491 164 277; fax: 33 (0) 491 164 270.
*E-mail address:* lasaygues@lma.cnrs-mrs.fr

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velocity measurement) of decay or sample [2]. In wood sample, the wave propagation process makes it necessary to add some signal processing tools, such as filtering, wavelet analysis, or deconvolution [3]. The chirp-coded excitation method [4], may be consider as an alternative method, successfully used in the medical field [5–7]. The main advantage for ultrasounds is that the use of coded waveforms improves signals (or image) quality (signal-to-noise ratio and dynamic). In the field of examination of wood, the technique could allow us to transmit a higher energy field, thus improving the penetration of the wave [8]. However, extend the temporal duration of the signal causes a loss of resolution on the determination of the time-of-flight (TOF) of the wave, and then, of the physical parameters. This article explores the ability in chirp-coded excitation in order to improve the measurement of the apparent thickness and ultrasonic wave velocity propagated in wood specimen using 500 kHz-transducers. The effect of temporal durations (25, 50 and 100µs) of the chirp waveform on the accuracy of the measurement was studied for three wood species parallelepipedic samples (Iroko, Tatajuba and Pine), and for a calibrated resin sample as reference one. Results obtained with the chirp-coded excitation method were compared to those obtained with the pulse-mode method.

## 2. Methods and experiments

### 2.1. The ultrasonic measurement

The experiment was conducted in transmission mode and two transducers with the same centre frequencies of 500 kHz were used. The thicknesses and velocities were calculated using a conventional ultrasonic pulse-mode method (which will be called "PM-method" from now on) to obtain control data, and using the chirp-coded excitation method (which will be called "CCE-method" from now on). The PM-method is described in [9], and CCE-method in [10]. With the CCE-method, the transmission signal is digitized in order to simultaneously measure the first TOF $t_1$ of the transmitted wave from the transmitter to the receiver crossing the sample, and the second TOF $t_2$, crossing two times the sample after the back-wall echo. The thickness (e) and the velocity ($V_e$) are given by:

$$\text{(a)}\quad e = V_{ref}\left[t_0 - \frac{3t_1 - t_2}{2}\right] \qquad \text{(b)}\quad V_e = V_{ref}\left[\frac{2t_0 - 3t_1 + t_2}{t_2 - t_1}\right] \qquad (1)$$

$V_{ref}$ is the reference velocity of ultrasound in water.

Since the electro-acoustic device and the transducers therefore served as a continuous linear stationary causal filter, the input and output signals are connected by convolution (noted $\otimes$):

$$\text{(a)}\quad u(t) = (x \otimes h_M)(t) \qquad \text{(b)}\quad x(t) = (h_T^* \otimes s)(t) \qquad (2)$$

with $h_M(t)$ is the response of the object. 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-acoustic transfer function. In the transmission mode, without the sample, the response $h_M(t)$ in water depends, with no distortions of the propagation, on the time-delay of the wave, which is proportional to the distance between the two transducers, and the velocity $V_{ref}$. The reference output signal is therefore equal to the input signal x(t), which is invariant by translation:

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

With the PM-method, the electric input signal s(t) was a pulse, mathematically modelling as a Dirac distribution δ(t), and the reference output signal can be modelling as a "copy" of the electro-acoustic transfer function [11]

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

### 2.2. The chirp-coded excitation method

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

$$\text{(a)}\quad c(t) = \sin(2\pi f_1 t + \pi k_0 t^2) \qquad \text{(b)}\quad k_0 = \frac{f_2 - f_1}{t_p} \qquad (5)$$

$k_0$ defines the rate of the frequency sweep during the chirp waveform. The temporal duration $t_p$ of the chirp waveform was 25, 50 and 100µs (Fig. 1) and the chirp frequency was swept from $f_1$ = 0.25MHz and $f_2$ = 1MHz.

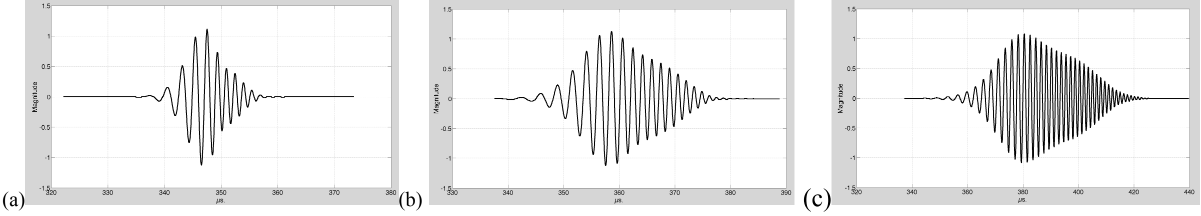

Fig. 1. Time graphs of transmitted-recorded chirp waveforms (500kHz), with different temporal durations, (a) 25µs, (b) 50µs (c) 100µs

The process of CCE-method is based on filtering of the transmitted signal by shaped-code filters, corresponding (in first intention) to the replica (inversed) electric input signal conveyed to the transmitter:

$$\gamma(t)=u(t)\otimes s(-t)=\left(h_M\otimes h_T^*\otimes s\right)(t)\otimes s(-t)=\left(h_M\otimes h_T^*\right)(t)\otimes R_{ss}(t) \Rightarrow \left[\gamma(t)\right]^{ref}=h_T^*(t)\otimes R_{ss}(t) \qquad (6)$$

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

## 3. Results and discussion

Experiments were conducted on one resin samples (170x110mm, $e_{ref}$ = 18.00+/-0.14mm) and three wood species samples (130x60mm); *Bagassa guianensis* – Tatajuba ($e_{ref}$ = 10.27±0.018mm), *Milicia excelsa* – Iroko ($e_{ref}$ = 9.55±0.067mm), and *Pinus spp.* – Pine ($e_{ref}$ = 10.47±0.037mm). All samples were obtained cutting, as rectangular and parallelepipedic plate, to the radial direction of tree's fibres using a scroll saw. The velocity in water ranged from $V_{ref}$ = 1490.9m/s to 1491.5m/s. Fig. 2.a shows the signal transmitted through the resin sample for a chirp generated with a temporal duration of 25µs. Fig. 2.b shows the cross-correlation with the generated signal. This correlation is done for all chirp waveforms and all samples. From these signals, the measurement of TOF $t_1$ and $t_2$ is performed, to calculate thicknesses and velocities (Table 1).

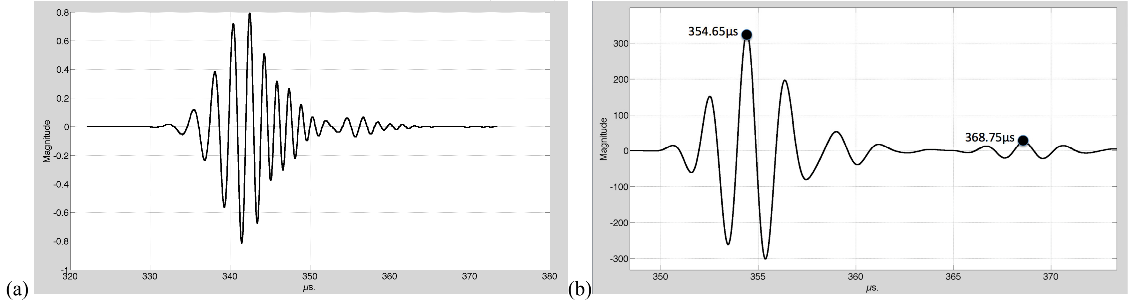

Fig. 2. (a) 25µs-chirp waveform transmitted through the resin sample; (b) Cross-correlation with the generated 25µs-chirp waveform

Table 1. Thicknesses and velocities obtained with each of the rectangular parallelepiped wood plates using a caliper, the PM-method and the CCE-method with different temporal durations 25, 50 and 100µs. (*) Relative error: $\delta x=\frac{\Delta x}{x}$

| Method | Samples | Resin | Tatajuba | Iroko | Pine |
|---|---|---|---|---|---|
| *PM* | *Thickness; Error*/calliper* | *18.18mm;1%* | *10.36mm; 0.88%* | *9.58mm; 0.31%* | *10.55 mm; 0.76%* |
| | Velocity | 2516m/s | 2134m/s | 1806m/s | 1563m/s |
| *25µs-chirp* | *Thickness; Error*/calliper* | *17.98mm; 0.11%* | *10.29mm; 0.19%* | *9.02 mm; 5.55%* | *10.35 mm; 1.15%* |
| | Velocity; Error*/PM (%) | 2551m/s; 1.37% | 2102m/s; 1.52% | 1792m/s; 0.78% | 1592m/s; 1.82% |
| *50µs-chirp* | *Thickness; Error*/calliper* | *18.09mm; 0.5%* | *10.39mm; 1.17%* | *8.98 mm; 5.97%* | *10.85 mm; 3.63%* |
| | Velocity; Error*/PM | 2558m/s; 1.64% | 2059m/s; 3.64% | 1780m/s; 1.46% | 1605m/s; 2.62% |
| *100µs-chirp* | *Thickness; Error*/calliper* | *18.28mm;1.53%* | *10.46mm; 1.85%* | *10.20 mm; 6.81%* | *10.96 mm; 4.68%* |
| | Velocity; Error*/PM | 2554m/s; 1.49% | 2062m/s; 3.49% | 1786m/s; 1.12% | 1612m/s; 3.04% |

For thicknesses and for all samples, the relative error increases as the temporal duration of the chirp waveform increases, but there are differences between the samples themselves, and between temporal duration. Several reasons may explain differences, but, since the thickness varied little from one part of the samples to another, the mean thickness was more precise using a calliper, and found to differ from the thickness at the ultrasonic measurement point because the ultrasonic beam, larger than the size of the calliper, is more sensitive to heterogeneities of the medium. For the measurement of velocities, results are presented some similarities with the previous one, but also differences, such as for the sample of Iroko, and there are possible reasons for this misfit, related to the material, or the method. The wood samples were cut in the radial direction of tree fibres. The propagation of the wave was collinear to this direction. At 500kHz, the wave continued to propagate through a homogeneous structure. However, due to the ring curvature of the tree, a gradient of the mechanical properties can exist, but differ from one sample to another. Moreover, wood samples were anisotropic which is of great importance for estimating, and will influence the distribution of the energy of the waves and then, the quality of signals. Another significant reason can be derived by comparing Eq.(1). In the numerator of Eq.(1.a) (thickness), the uncertainty is mainly from the small difference calculated from three TOFs. In Eq.(1.b) (velocity), the differences of TOFs appear in both numerator and denominator. This ratio may reduce the influence of small difference between the TOFs and yield less sensitivity to the measured values. Remark: Compared to the previous published results [12], a common difference of 500m/s exists for the mean wave velocities. This difference was mainly due to the difference between the wood samples used in the present study and those of Arciniegas *et al.*, which were taken from similar wood species (Tatajuba and Iroko), but in other parts of the tree.

## 4. Conclusion

The accordance of the thickness and velocity measurements may arise from two characteristics in the CCE-method using 500kHz-transducers. Firstly, the lower frequency applied in the method results in lower attenuation and induces better signals with higher signal-to-noise ration. Secondly, the methodology genuinely provides more accurate estimated TOF and leads to the better assessment for geometrical and acoustical parameters. Above all, it is indicated that the CCE-method is a more consistent and robust approach for parameter estimation. But the temporal duration of the chirp waveform is important to control. In this study, the results are more homogeneous working with a 25µs-chirp waveform. The relative error compared to conventional measures is lower. For temporal durations higher than 25µs-chirp waveform, the error increases. To continue this work, there should be a thorough study of wave attenuation as a function of the distance from the transducer. It should also work with samples whose surface condition would not be machined.

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