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

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13 **ABSTRACT**

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

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

34 Experiments were conducted on a polyurethane resin sample and two samples of
35 different wood species using two 500 kHz-transducers. The relative errors in the
36 measurement of thickness compared with the results of caliper measurements
37 ranged from 0.13% minimum for the wavelet-coded excitation method to 2.3%
38 maximum for the chirp-coded excitation method. For the relative errors in the

39 measurement of ultrasonic wave velocity, the coded excitation methods showed
40 differences ranging from 0.24% minimum for the wavelet-coded excitation method
41 to 2.62% maximum for the chirp-coded excitation method. Methods based on coded
42 excitation algorithms thus enable accurate measurements of thickness and
43 ultrasonic wave velocity in samples of wood species.

44

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

47 INTRODUCTION

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

68 Techniques for transmitting encoded waveforms, such as the chirp-code excitation
69 method, are potential alternatives of great interest in the field of acoustical imaging,
70 and in particular for medical ultrasounds [6]–[9]. Used for the examination of living
71 trees, the technique would allow a higher energy field to be transmitted, thus
72 improving the penetration of the wave [10]. However, prolonging the signal reduces
73 the resolution of the determination of the arrival times and the detection of the
74 different interfaces. Depending on the wavelength, this causes an overlap between
75 the wave packets that results in a significant loss of information. Lasaygues *et al.*
76 [11] showed that the duration of the chirp signal had a weak influence on the

77 calculation of physical parameters such as the thickness and the ultrasonic wave
78 velocity.

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

116 with a more conventional pulse method, based on a protocol requiring three
117 measurements for the calculation of the parameters.

118 **METHODS AND MATERIAL**

119 *Ultrasonic measurements*

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

133 The experiment was conducted in transmission mode using two transducers facing
134 each other with their axes aligned (Fig. 1). The transducers were moved linearly
135 over a distance of 80 mm and were positioned automatically from the right to the
136 left of the sample at 4 mm intervals (Fig. 2). At each position of the coupled
137 transducers (from 1 to 21), the sample thickness and the ultrasonic wave velocity in
138 the sample were calculated. The center frequency of both transducers (Imasonic®,
139 Voray sur l'Ognon, France) was 500 kHz. The sample was placed at the focal spot
140 (~150 mm from the transducer) parallel to the transducer surface. At the focal spot,
141 the active area (~400 mm²) of the transducer was smaller than the length and the
142 width of the parallelepiped sample. The total linear displacement (80 mm) of the
143 transducers is greater - and the pitch between two positions (4 mm) lower - than the
144 beam width (~20 mm). This choice makes it possible to calculate mean values and
145 standard deviations for several significant points per sample.

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

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

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

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

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

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

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

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

166 ***The pulse method***

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

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

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

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

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

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

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

$$186 \quad \text{Eq. 6} \quad v_e^2 = v_{ref}^2 \left[1 + \left(\frac{\tau v_{ref}}{e} \right) \left(\frac{\tau v_{ref}}{e} - 2 \right) \right]^{-1}$$

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

189 ***The chirp-coded excitation method***

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

$$192 \quad \text{Eq. 7} \quad s(t) = \left(1 - \cos \left[2\pi t / t_p \right] \right) \sin [2\pi f_1 t + \pi k_0 t^2]$$

193 $k_0 = \frac{f_2 - f_1}{t_p}$ defines the rate of the frequency sweep of the chirp waveform. The

194 duration t_p of the chirp waveform was 25.55 μs and the chirp frequency was swept
 195 between $f_1 = 0.25$ MHz and $f_2 = 1$ MHz. According the conclusions of our previous
 196 work [11], these values enabled a minimum error in the calculation of the physical
 197 parameters. The process of coded excitation is based on filtering of the transmitted
 198 signal by the replica (inversed) of the electric input signal conveyed to the
 199 transmitter (Fig.4):

$$200 \quad \text{Eq. 8} \quad \gamma(t) = u(t) \otimes s(-t) = \left(h_M \otimes h_T^* \otimes s \right) (t) \otimes s(-t) = \left(h_M \otimes h_T^* \right) (t) \otimes R_{ss}(t)$$

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

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

$$205 \quad \text{Eq. 9} \quad e = v_{ref} \left[t_0 - \frac{3t_1 - t_2}{2} \right]$$

206 and

$$207 \quad \text{Eq. 10} \quad v_e = v_{ref} \left[\frac{2t_0 - 3t_1 + t_2}{t_2 - t_1} \right]$$

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

213 The measurements were then carried out as follows:
 214 - One signal in transmission mode in the absence of a sample to obtain the time t_0
 215 and the reference ultrasonic wave velocity v_{ref} ;
 216 - One signal in transmission mode in the presence of sample to obtain the times t_1
 217 and t_2 . The first time t_1 was determined by searching for the first maximum of the
 218 function $\gamma(t)$, and the second time t_2 was determined on the second maximum of
 219 the function corresponding to the back wall echo.

220 ***The wavelet-coded excitation method***

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

$$225 \text{ Eq. 11 } u(t) = (\varphi_J \otimes h_M)(t)$$

226 The coded-excitation method is then based on a time-scale decomposition of the
 227 signal $u(t)$ giving the suitable coefficients $X_j(t)$:

$$228 \text{ Eq. 12 } X_j(t) = \langle u(t), \varphi_j(t) \rangle = h_M(t) \otimes [\varphi_J \otimes \varphi_j](t)$$

229 where φ_j is a wavelet centered on the scale j ($\forall j \in \mathbb{Z}$). The properties of the wavelet
 230 decomposition (an orthogonal decomposition in this work) are such that the
 231 coefficients $X_j(t)$ nullify everywhere except for $j = J$.

$$232 \text{ Eq. 13 } X_j(t) = X_J(t) = h_M(t) \otimes \delta(t) = h_M(t)$$

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

$$237 \text{ Eq. 14: } u(t) = A_1 \varphi_J(t - t_1) + A_2 \varphi_J(t - t_2)$$

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

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

$$243 \text{ Eq. 15: } X_j(t) = A_1 \langle \varphi_J(t - t_1), \varphi_j(t) \rangle + A_2 \langle \varphi_J(t - t_2), \varphi_j(t) \rangle$$

$$244 \text{ Eq. 16: } X_j(t) = X_j(t - t_1) + X_j(t - t_2)$$

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

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

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

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

$$262 \text{ Eq. 17 } s(t) = \varphi_J(t) \otimes [u(t)]^{ref}$$

263 where \otimes denotes the operation of deconvolution.

264 As shown in Fig. 3, the fit between the experimental and theoretical curves is
265 correct, except around the nominal frequency. The effect on the temporal signal is
266 negligible, and does not influence the resolution of the TOF detection algorithm.

267 At this stage, it is worth noting that the chirp- and the wavelet-coded excitation
268 methods require only one transmitted signal for calculation of the velocity and
269 thickness of the ultrasonic wave, whereas the pulse method requires three signals
270 (1 transmitted and 2 reflected signals). For the pulse method, the calculation of the
271 ultrasonic wave velocity depends on the measurement of thickness, and therefore
272 on measurement error. For the protocol used for the chirp- and wavelet-coded
273 excitation method, the two parameter calculations are independent.

274 ***Samples preparation***

275 Experiments were conducted on one polyurethane resin sample (length = 170 mm,
276 width = 110 mm, thickness = 18.34 ± 0.01 mm, density = 1165 kg/m^3) and two
277 samples of wood species (length = 130 mm, width = 60 mm): Tatajuba, *Bagassa*
278 *guianensis* (thickness = 10.27 ± 0.02 mm, density = 800 kg/m^3), and Iroko, *Milicia*
279 *excelsa* (thickness = 9.55 ± 0.07 mm, density = 640 kg/m^3) (Fig. 5). All the samples
280 were prepared in the form of rectangular parallelepiped-shaped plates by cutting in
281 the radial direction of tree fibers using a scroll saw (Rexon[®] BS10, Taiwan), and

282 were tested in the ultrasonic experiments at a moisture content above 30%. The
283 reference average thicknesses at five arbitrary points near the middle of the samples
284 were measured using a caliper (Absolute Digimatik Solar[®], Mitutoyo, Kanagawa,
285 Japan). Control values for the thicknesses are given in the Table 1.

286 **RESULTS AND DISCUSSION**

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

299 For the chirp-coded excitation method, the times t_1 and t_2 were obtained by
300 subtracting the duration of the chirp function (25.55 μ s) from the measured times
301 of ultrasonic waves propagating from the transmitter to the receiver in the presence
302 of a sample (e.g. for the resin sample, $t_1 = 354.65$ μ s - 25.55 μ s = 329.10 μ s; $t_2 =$
303 368.75 μ s - 25.55 μ s = 343.20 μ s (Fig. 7)).

304 For the wavelet-coded excitation method, the times t_1 and t_2 were measured by cross
305 correlating the output signal $u(t)$ with an analyzing wavelet pattern. Fig. 8 shows
306 the result in the case of the resin sample. The time t_1 of the first transmitted signal
307 is equal to that obtained by the chirp-coded excitation method ($t_1 = 329.10$ μ s). The
308 time t_2 of the second signal is equal to 343.60 μ s. It is not located exactly at the
309 maximum of the wave packet. The times measured by the wavelet-coded excitation
310 method do not always correspond to maximum energy. The pulse method and chirp-
311 coded excitation method allow to determine the times corresponding to the
312 maximum energy of the wave packets. The result depends on the transmitted
313 energy, and the measured times correspond to maximum energy levels. The
314 wavelet-coded excitation method uses the mathematical properties of the wavelet
315 function and of the orthogonal decomposition, regardless of the transmitted energy.
316

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

- 320 - a caliper for reference thicknesses;
- 321 - the pulse method for reference ultrasonic wave velocities;
- 322 - the chirp-coded excitation method with the duration of the chirp function of
323 25.55 μ s;
- 324 - the wavelet-coded excitation method with the wavelet centered on the fixed scale
325 $J = -5$.

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

328 For the measurement of the thicknesses (Fig. 9), the relative errors comparing the
329 physical and ultrasonic measurements in the case of the pulse method were similar,
330 around 1%. The relative errors for the resin and Iroko samples were higher than
331 those for the Tatajuba sample. Whatever the sample, the thickness measurements
332 using the chirp-coded excitation method involved a significant increase in relative
333 errors compared with the pulse method and wavelet-coded excitation method,
334 ranging from 1.91% (resin) to 2.30% (Iroko). The relative error of the wavelet-
335 coded excitation method was lower than that of the other methods, ranging from
336 0.33% (resin) to 0.63% (Iroko). The wavelet-coded excitation method was found to
337 be more accurate than the pulse method or the chirp-coded excitation method for
338 the evaluation of sample thickness.

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

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

355 produced better results than the chirp-coded excitation method for the samples of
356 wood species than for the resin sample.

357

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

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

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

388 Samples of wood species are orthotropic whereas the resin sample is assumed to be
389 isotropic. The anisotropy of the sample is extremely important for the estimation of
390 the physical parameters and influences the distribution of the energy of the waves
391 and the quality of the transmitted and reflected signals, whatever the method used.
392 To summarize, the wavelet-coded excitation method is less sensitive to the
393 heterogeneity and the anisotropy of the medium than the chirp-coded excitation
394 method. The 25.55 μ s-chirp wave is slightly resolved in the axial plane of the

395 ultrasonic beam. In Eq. 8, the signal is filtered by the response of the transducer,
396 which may also introduce even a slight distortion. The cross correlation makes it
397 possible to solve the inverse problem of detection of TOF. Conversely, in Eq. 13,
398 the wavelet-coded excitation method allows the signal to be adapted to the
399 electronic system. The recorded signal depends only on the response of the medium.
400 The axial resolution is better and less sensitive to changes in the structure of the
401 medium. The relative error on the final measurements of the parameters is smaller,
402 and the wavelet-coded excitation method could be the best way to improve
403 measurement accuracy.

404 CONCLUSIONS

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

432 choice of a specific wavelet function, and then the calibration process are
433 fundamental steps in the in-situ application of the method.

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502 Table 1: Mean values and standard deviations of the thicknesses and velocities
503 calculated for 21 transducer positions (distance: 80 mm, pitch: 4 mm) for each of
504 the rectangular parallelepiped samples using a caliper, the pulse method, the chirp-
505 coded excitation method with the duration of the chirp function of 25.55 μs , and the
506 wavelet-coded excitation-coded excitation method. (*) Relative error: $\delta x = \frac{\Delta x}{x}$.
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509 Fig. 1: Overview of the ultrasonic measurement set-up: mechanical scanner, 500
510 kHz-transducers (Imasonic[®]); sample between transmitter and receiver; water tank.

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

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

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

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

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

533 Fig. 7: Cross-correlation $\gamma(t)$ between the transmitted signal through the resin
534 sample and the generated chirp waveform with a duration of 25.55 μs . (Dark circle)
535 Measurement of the T.O.F. $t_1 = 354.65 \mu\text{s} - 25.55 \mu\text{s} = 329.10 \mu\text{s}$; $t_2 = 368.75 \mu\text{s} -$
536 $25.55 \mu\text{s} = 343.20 \mu\text{s}$.

537 Fig. 8: Signal transmitted through the resin sample when the electric input signal is
538 a wavelet waveform ($J = -5$). (Dark circle) Measurement of the T.O.F. $t_1 = 329.1$
539 μs , and $t_2 = 343.6 \mu\text{s}$, using the algorithm developed by Loosvelt and Lasaygues
540 [14].

541 Fig. 9: Relative error (%) of the mean values of the thickness measurements,
542 between the measurement using a caliper (as reference) and measurement using the
543 pulse method, the chirp-coded excitation method with a duration of $25.55 \mu\text{s}$, and
544 the wavelet-coded excitation method.

545 Fig. 10: Relative error (%) of the mean values of the ultrasonic wave velocity
546 measurements between the measurement using the pulse method (as reference
547 method) and the measurement using the chirp-coded excitation method with a
548 duration of $25.55 \mu\text{s}$, and the wavelet-coded excitation method.