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1 **Ultrasound computed tomography on standing**
2 **trees: accounting for wood anisotropy permits a**
3 **more accurate detection of defects**

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10

11 **Key Message**

12 Considering anisotropy in image reconstruction algorithm for ultrasound computed tomography
13 of trees resulted in a more accurate detection of defects compared to common approaches used.

14 **Abstract**

15 **Context**

16 Ultrasound computed tomography is a suitable tool for nondestructive evaluation of standing
17 trees. Until now, to simplify the image reconstruction process, the transverse cross-section of
18 trees has been considered as quasi-isotropic and therefore limiting the defect identification
19 capability.

20 **Aims**

21 An approach to solve the inverse problem for tree imaging is presented, using an ultrasound-
22 based method (travel-time computed tomography) suited to the anisotropy of wood material and
23 validated experimentally.

24 **Methods**

25 The proposed iterative method focused on finding a polynomial approximation of the slowness in
26 each pixel of the image depending on the angle of propagation, modifying the curved trajectories
27 by means of a raytracing method. This method allowed a mapping of specific elastic constants
28 using nonlinear regression. Experimental validation was performed using sections of green wood
29 from a pine tree (*Pinus pinea L.*), with configurations that include a healthy case, a centered and
30 an off-centered defect.

31 **Results**

32 Images obtained using the proposed method led to a more accurate location of the defects
33 compared to the filtered back-projection algorithm (isotropic hypothesis), considered as
34 reference.

35 **Conclusion**

36 The performed experiments demonstrated that considering the wood anisotropy in the imaging
37 process led to a better defect detection compared to the use of a common imaging technique.

38 **Keywords:** *wood; orthotropy; ultrasonic; wave propagation*

39

40 **1. Introduction**

41 Due to its biological origin, the properties of wood have a high degree of variability. Trees are
42 indeed complex lignified plants with a morphology and internal structure marked by a high
43 heterogeneity that is structured by the genetic origin of the trees but also by their conditions of
44 management and environmental factors, including the climate. Characterizing wood properties
45 and inner heterogeneities of trees brings information useful for clonal selection, grading of logs,
46 but also for tree risk management in urban areas. Standing trees in urban areas present an
47 important ecological and health role (Pokorny, 2003). The tree population requires control and
48 management processes to assess potential risks. For example, falling trees pose a danger to
49 pedestrians, houses, and cars. Aiming to minimize the risk associated with tree failure, several
50 significant advances in decay-detection equipment, formulas, and guidelines for assessing
51 hazardous trees have been done (Johnstone et al. 2010; Leong et al. 2012).

52 The most common methods to evaluate the inner state of standing trees consist of drilling
53 measures or in acoustical or electrical spot measurements (Pellerin and Ross 2002). However,
54 these techniques remain limited, providing only one-dimensional information. To overcome this
55 limitation, nondestructive acoustic and ultrasonic imaging methods have been presented as an
56 alternative to carrying out the assessment of the inner structures of trees, without altering their
57 condition (Bucur 2003; Arciniegas et al. 2014a).

58 The most known commercial devices use acoustic waves, where a hammer is used as emitter.
59 Different studies have shown that these acoustic devices present different drawbacks, such as a
60 low spatial resolution, images difficult to interpret, detection precision not always optimal and a
61 relatively long time of execution (Rabe et al. 2004; Gilbert and Smiley 2004; Wang et al. 2007;
62 Deflorio et al. 2008).

63 The quality of the obtained image (time-of-flight tomography) is influenced by different aspects,
64 resulting from the interaction between transmitted waves and heterogeneous and anisotropic
65 media. This includes the frequency (sound or ultrasound), the signal to noise ratio, the
66 phenomena of attenuation and diffraction, the total number of sensors, the modeling and the
67 assumption of the propagation, and the image reconstruction algorithm (Arciniegas et al. 2014b).
68 The ultrasonic approach aims to increase the frequency of excitation to obtain images with higher
69 resolution.

70 The basic principle for Ultrasound Computed Tomography (USCT) is that decay inside wood
71 affects the propagation of elastic waves, leading to a decreasing velocity and an increasing

72 attenuation. The Fermat's principle states that the first-arriving wave, that of the compressional
73 wave, will tend to travel along the fastest path, therefore the presence of pronounced
74 compressional wave velocity contrasts will tend to curve the rays (Maurer et al. 2005). Decay
75 regions will be avoided, as they slow down waves, resulting in larger time-of-flight (TOF)
76 measurements compared to healthy wood.

77 USCT of wood was first presented by Tomikawa et al. (1986), aiming to perform non-destructive
78 testing of wooden poles. TOF measurements were obtained considering a fanbeam geometry
79 and the filtered backprojection algorithm for image reconstruction. It was found that the proposed
80 USCT algorithm and device were adequate to detect rotten areas, but some drawbacks were
81 highlighted, such as a weak image resolution and long computation time. Afterward, different
82 approaches have been presented (Martinis et al. 2004; Lin et al. 2008; Brancheriau et al. 2008;
83 Brancheriau et al. 2011). It was pointed out that ultrasonic techniques are suitable for standing
84 trees quality evaluation, using frequencies ranging from 22 kHz to 1 MHz, enabling to detect
85 decay, knots, fungal attack, and other defects. Up to now, these approaches have not considered
86 the anisotropy property of wood in a mechanical modeling of wave propagation, affecting the
87 image reconstruction. To build the tomographic image, it is necessary to know the trajectories
88 (rays) followed by the waves from the transmitter to each receiver. As shown in different studies,
89 wood anisotropy leads to deformed wavefronts, compared to the spherical wavefronts obtained
90 for isotropic media (Payton 2003; Schubert et al. 2008; Gao et al. 2014; Espinosa et al. 2019a).
91 This deformation leads to curved trajectories (Maurer et al. 2006), compared to the straight-line
92 trajectories under isotropic condition. These curved trajectories should be considered for a
93 suitable reconstruction.

94 This study aimed to consider the anisotropy property of wood in the tomography image
95 reconstruction process, by developing an iterative method that takes into account the curved ray
96 paths. This inversion procedure allowed determining locally the specific elastic constants of the
97 wood material. We proposed an experimental configuration to evaluate the precision of defect
98 detection using the proposed image reconstruction technique, compared to a common method
99 that considers a straight-line hypothesis (filtered back-projection algorithm). The proposed
100 inversion procedure was tested in a pine sample, considering three cases: a healthy case, a
101 simulated centric defect case, and a simulated eccentric defect case. Results will be discussed
102 according to several criteria with the aim of applying the method with a view to in situ operations:
103 the computing time with a common computer, the number of probes and sensors, and the
104 possibility to implement the proposed method in the existing commercial devices.

105

106 **2. Materials and methods**

107 **2.1. Wood samples**

108 From a healthy trunk of a pine tree (*Pinus pinea L.*), 3 wood disks were obtained. The disk
109 diameter was 24 cm and the thickness of each disk was 3 cm. The tree age was 55 years. To
110 reduce water loss during experiments, logs were sealed and stored in a temperature-controlled
111 room (+4°C). The average moisture content was 92% (moisture reduction during the tests was
112 less than 3%).

113 To simulate the presence of a defect, a circular hole was drilled with a diameter of 7.6 cm. Two
114 defect positions were tested: centered and off-centered (halfway between the center and the
115 bark). Even when the tree section used for testing did not present any decay, there was a
116 presence of reaction wood and juvenile wood, that affects the physical and mechanical properties
117 (Timell 1986; Ross 2010; Gardiner et al. 2014), and consequently the propagation of waves
118 (Bucur 2006; Brancheriau et al. 2012).

119 **2.2. Ultrasonic testing**

120 Ultrasonic measurements were obtained at 16 different positions around the wood disks,
121 distributed uniformly. To validate experimentally the image reconstruction procedure, it was
122 decided to debark the disks in order to improve the coupling of the sensors (to increase the energy
123 transfer and the quality of the signals); this avoided bias not due to the inversion procedure itself.
124 The ultrasonic chain of measurement is shown in Fig. 1. The ultrasonic (US) sensors had a main
125 resonant frequency at 60 kHz (Physical Acoustics Corporation R6α). To improve energy transfer,
126 a fluid couplant was used. The electro-acoustical set-up consisted of a signal generator and an
127 oscilloscope (Picoscope 2000), connected to a PC for data acquisition. Additionally, two electronic
128 amplifiers were used, one located after the signal generator (Single Channel High Voltage Linear
129 Amplifier A800, FLC Electronics) to increase the energy sent to the US transmitter, and other at
130 the US receiver output (Physical Acoustics Corporation AE2A/AE5A), both with an amplification
131 of 40 dB. The excitation signal was a chirp signal (central frequency of 60 kHz, bandwidth of 48
132 kHz), leading to a concentrated power spectrum around the sensor central frequency that allows
133 a time-of-flight (TOF) measurement using a cross-correlation (Espinosa et al. 2018b). The full set
134 of TOF measurements (i.e. projections) was obtained by placing the transmitter at the 16 different

135 points along the wood disk circumference. For every transmitter position, the receiver position
136 changed in the remaining 15 points.

137 **2.3. Inversion procedure**

138 It is necessary to establish the mathematical model allowing to express the relation between the
139 ultrasonic measurements and the inner mechanical wood parameters. The inverse problem
140 consists in finding the model parameters from a set of measurements.

141 Considering the transversal section of a trunk (2D case), wood mechanical properties are
142 determined by two perpendicular axes: the radial axis (R) aligned from the bark to the pith and
143 the tangential axis (T), tangent to the growth rings. The stress (σ) and strain (ε) relations are given
144 by the Hook's law, with the rigidity matrix C for an orthotropic material. For the RT plane, the
145 elastic parameters are Young's moduli E_R (radial direction) and E_T (tangential direction), the shear
146 modulus G_{RT} and the Poisson's coefficient ν_{RT} .

147 As time-of-flight (first arrival) tomography was considered, therefore only pure compression waves
148 were considered (hereinafter refers to as ultrasonic waves), omitting all other second-order
149 phenomena (refraction on the defect, shear waves regardless of the incidence conditions, mode
150 conversion, amplitude modification, and dispersion). The ultrasonic wave velocity V in wood
151 depends on the direction of propagation θ , the elastic parameters and the wood density as
152 expressed by the Christoffel equation (Espinosa et al. 2018):

$$\begin{aligned}\Gamma_{RR} &= C_{11} \cos^2 \theta + C_{66} \sin^2 \theta, \\ \Gamma_{TT} &= C_{66} \cos^2 \theta + C_{22} \sin^2 \theta, \\ \Gamma_{RT} &= (C_{12} + C_{66}) \cos \theta \sin \theta, \\ V &= \sqrt{\frac{\Gamma_{RR} + \Gamma_{TT} + \sqrt{(\Gamma_{TT} - \Gamma_{RR})^2 + 4 \cdot \Gamma_{RT}^2}}{2\rho}}.\end{aligned}\tag{1}$$

153 The θ angle is formed between the direction vector n (normal to the wavefront) and the radial (R)
154 direction (Fig. 2). Then, higher velocities are obtained for waves propagating in the radial direction
155 ($\theta=0^\circ$) compared to the tangential direction ($\theta=90^\circ$). Therefore, wavefronts are not strictly circular
156 as for the case of isotropic materials, resulting in curved trajectories between the transmitter and
157 each receiver (Espinosa et al. 2019a).

158 For image reconstruction, it is necessary to know the real trajectories (or ultrasonic ray paths).
159 This process considers a space divided into cells (or pixels), that are traversed by the rays. The
160 objective is to estimate a local slowness α for every cell. The addition of individual slowness values

161 along the ray leads to the TOF measurement at the receiver (Eq.2). For a given pair transmitter-
 162 receiver, which trajectory m crosses k cells, the time-of-flight t_m can be written as:

$$t_m = \sum_{k \text{ along } m} l_{mk} \alpha_k \quad (2)$$

163 With l_{mk} as the length of the ray segment. Solving all the equations for α results in the
 164 reconstruction of the inner parameter (inverse problem). Two considerations arise at this point:
 165 first, the matrix formulation should be adapted to consider the slowness dependency on the angle
 166 of propagation, and second, the estimation of the curved trajectories, a priori unknown, affected
 167 by the wood anisotropy and the presence of defects (slow propagation regions).

168 In many algebraic reconstruction techniques, the l_{mk} terms are replaced by 1's and 0's, depending
 169 on whether or not the image cell is traversed by the m ray (more details in Kak and Slaney 2001).
 170 The total length of a ray L_m is then considered as the sum of individual ray segments l_{mk} ,
 171 assuming these segments to be uniform. We have $L_m = D_m l_m$, with D_m as the total number of ray
 172 segments in the path m . Dividing both sides of Equation 2 by L_m we have:

$$A_m = \frac{t_m}{L_m} = \frac{1}{D_m} \sum_{k \text{ along } m} \alpha_k \quad (3)$$

173 with A_m as the total slowness of the ray. So, for every pair of transmitter-receiver, an equation
 174 can be formulated, resulting in a system of linear equations. To adapt the matrix formulation to
 175 consider the slowness dependency on the angle of propagation, the Christoffel equation was
 176 approximated by a polynomial function of the angle of propagation (5th degree). This polynomial
 177 was selected from an R^2 evaluation using different degrees, allowing the determination of the
 178 specific elastic parameters of the Christoffel equation (Espinosa et al. 2020). Then, the slowness
 179 for a pixel k crossed by a ray m was written as:

$$\alpha_k = \beta_{5,k} \theta_{k,m}^5 + \beta_{4,k} \theta_{k,m}^4 + \beta_{3,k} \theta_{k,m}^3 + \beta_{2,k} \theta_{k,m}^2 + \beta_{1,k} \theta_{k,m}^1 + \beta_{0,k} \theta_{k,m}^0, \quad (4)$$

180 The inverse problem solution corresponded to find the polynomial coefficients β for all the pixels.
 181 Combining equations 3 and 4 for every pixel, we obtain a set of linear equations, as presented in
 182 Equation 5. The SIRT (Simultaneous Iterative Reconstruction Technique) method was used to
 183 solve this matrix problem (Kak and Slaney, 2001). To increase the number of equations, an
 184 interpolation of the TOF measurements was done. Virtual sensors were located between the
 185 original ones, passing from 16 sensors to 32 sensors, by linear interpolation of the TOF
 186 measurements and the positions of the sensors. The choice of an interpolation to 32 sensors was
 187 linked to a previous research showing that reconstruction algorithms such as SIRT (used in the

188 proposed method) converged from 30 transducer positions (Arciniegas et al. 2014b). The
 189 sinogram interpolation has shown to be an alternative to increase the defect identification capacity
 190 when using a limited number of sensors (Espinosa et al. 2019c).

$$\begin{bmatrix} \theta_{1,1}^5 & \cdots & \theta_{1,1}^0 & 0 & \cdots & 0 & \cdots & \theta_{N,1}^5 & \cdots & \theta_{N,1}^0 \\ 0 & \cdots & 0 & \theta_{2,2}^5 & \cdots & \theta_{2,2}^0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \theta_{1,M}^5 & \cdots & \theta_{1,M}^0 & 0 & \cdots & 0 & \cdots & \theta_{N,M}^5 & \cdots & \theta_{N,M}^0 \end{bmatrix} \begin{bmatrix} \beta_{5,1} \\ \vdots \\ \beta_{0,1} \\ \beta_{5,2} \\ \vdots \\ \beta_{0,2} \\ \vdots \\ \beta_{5,N} \\ \vdots \\ \beta_{0,N} \end{bmatrix} = \begin{bmatrix} D_1 A_1 \\ D_2 A_2 \\ \vdots \\ D_m A_m \end{bmatrix}, \quad (5)$$

191 For the estimation of the curved trajectories, an initial guess corresponded to straight-line paths.
 192 With this initial guess, it was possible to perform a first inversion process, leading to the polynomial
 193 coefficients β of the slowness for all the pixels. Using these coefficients, we can perform a
 194 numerical simulation to obtain an estimation of the TOF and the trajectories. The model used for
 195 the simulation of the forward problem corresponded to a raytracing approximation (Espinosa et
 196 al. 2019a, Espinosa et al. 2019b). This process was repeated until the TOF and trajectories
 197 difference with respect to the model was minimized.

198 From the polynomial approximation obtained for every pixel, the values of the specific elastic
 199 constants could be estimated using a nonlinear least square regression (Seber and Wild 1989).
 200 The result is an image of an elastic parameter of wood. In this case, it was decided to determine
 201 the Young's modulus in the radial direction (E_R) for a given density value (E_T and G_{RT} can also be
 202 computed with the proposed procedure). The proposed inversion schema is shown in Fig. 3.

203 2.4. Assessment of decay detection

204 To evaluate the improvement in the image reconstruction by considering the wood anisotropy, a
 205 comparison was made with images obtained using an algorithm that considers an isotropic and
 206 straight-line rays' assumptions. The analytical method was based on the sum of the inverse
 207 Fourier transforms of the filtered back-projections (so-called FBP method) (Kak and Slaney,
 208 2001). The sinograms used for the FBP method were also interpolated. From each image a profile
 209 is presented, which crosses the center of the disk.

210 The images for the defective cases were segmented using a threshold. It has been previously
 211 shown that using a threshold value to separate healthy and defective regions is not always the
 212 most suitable way of interpreting tomograms (Espinosa et al. 2017). In this specific case, the

213 thresholding segmentation was chosen because it allowed comparing quantitatively the two
214 image reconstruction methods. The threshold values corresponded to 30%, 50%, 70% and 90%
215 of the mean value from the reconstructed image. To assess the defect discrimination capability,
216 two statistical measurements were obtained: the sensitivity or true positive rate (TP) and the fall-
217 out or false positive FP rate. The first is computed as the ratio of correctly identified pixels inside
218 the defective area; for correct identification, expected values should be as near as possible to
219 100%. The second corresponds to the ratio of incorrectly identified pixels, i.e. the pixels classified
220 as a defect, that are outside the defective area; for correct identification, expected values should
221 be as near as possible to 0%.

222

223 **3. Results**

224 **3.1. Healthy case**

225 First, a healthy disk was tested. The cross-section is shown in Fig. 4a, drawing attention to the
226 presence of compression wood (right area in the image). After performing the tomographic
227 reconstruction using the proposed method and the reference FBP method, the corresponding E_R
228 parametric image, and the reference velocity image are presented in Fig. 4b and Fig. 4c
229 respectively. For the E_R image, the mean value was 1258 MPa, with a standard deviation of $\sigma=126$
230 MPa. For the FBP image, the mean velocity was 1551 m/s with $\sigma=315$ m/s. Even when both
231 images presented relatively flat surfaces, the FBP image presented more artifacts near to the
232 borders, where the precision of the TOF measurements is lower (Espinosa et al. 2018b). Two
233 horizontal profiles traversing the center of the image are shown in Figs. 4d and 4e, for the E_R
234 parametric image and the reference velocity image respectively. The profile obtained in Fig. 4d
235 presents three different parts: in the left, E_R values corresponding to normal wood, then around
236 the pith, lower E_R values, that could be associated with the presence of juvenile wood, and in the
237 right, higher E_R values for the part with compression wood.

238 Juvenile wood density is lower than the mature one (Ross 2010). This can be associated with the
239 presence of thinner cell walls and shorter tracheids in juvenile wood. Another characteristic of
240 juvenile wood is a large microfibril angle that might be associated with low stiffness and a low
241 Young's modulus (Barnett and Bonham 2004). Juvenile wood has also been associated with a
242 decreased velocity of ultrasonic waves (Brancheriau et al. 2012a; Palma et al. 2018). This wood
243 is often considered as low-quality for many industrial uses as it typically presents low strength
244 properties (Senft et al. 1985).

245 In the case of compression wood, density is higher compared to normal wood, given that the cell
246 wall is much thicker (Timell 1986; Kollmann and Côté 2012). With the proposed method, regions
247 affected by these density changes could lead to a biased value, considering that a single density
248 value was fixed for the whole disk. Compression wood also has a greater microfibril angle
249 compared to normal wood, leading to a higher stiffness in the RT plane and lower stiffness in the
250 longitudinal direction (Brancheriau et al. 2012b; Gardiner et al. 2014). Then, the velocity of
251 propagation of ultrasonic waves in compression wood is higher compared to normal wood
252 (Saadat-Nia et al. 2011; Brancheriau et al. 2012b). This effect has been used for the detection of
253 compression wood using ultrasound in previous approaches (Bucur 2006).

254 **3.2. Centered and off-centered defects**

255 For the centered defect position, the tested disk is shown in Fig. 5a. The hole drilled to simulate
256 the defect was centered with respect to the pith, that was not located in the geometric center of
257 the disk, due to the presence of compression wood. In Fig. 5b, the trajectories computed iteratively
258 in the inversion procedure are shown; and it is possible to observe how after convergence of the
259 method these trajectories avoid the defective area. The reconstructed images obtained with the
260 proposed method and the FBP method are shown in Fig. 5c and Fig. 5d respectively. The
261 proposed method allowed a more detailed defect identification, as the void region is distinct
262 compared to the smooth variation obtained with the FBP image. This enhanced contrast between
263 the defect and the healthy wood using the proposed method is linked to the use of curved rays,
264 considering this kind of trajectories avoid the low-speed propagation areas. In contrast, the FBP
265 method tends to smooth the output image (Kak and Slaney, 2001). The corresponding horizontal
266 profiles are shown in Fig. 5e and Fig. 5f. These profiles corroborate that the defect shape is better
267 approximated with the proposed method, resulting in sharper defect borders.

268 To compare quantitatively the ability of defect detection, the thresholding process was applied.
269 Fig. 6 presents the thresholding results, based on the mean values in the reconstructed images.
270 The mean velocity in the FBP image was 1527 m/s ($\sigma=553$ m/s). For the E_R image, the mean
271 value was 1361 MPa ($\sigma=289$ MPa). In the case of the FBP image, using the first two threshold
272 values, no defect was found. For the threshold values of 70% and 90%, the true positive rate was
273 33% and 96% respectively, with false-positive rates of 7% and 29%. Improvements were obtained
274 using the proposed method (E_R image), with true-positive rates of 61%, 66%, 75% and 95% as
275 the threshold value increased, and false-positive rates of 5%, 8%, 11%, and 25% respectively.
276 The E_R image with a threshold of 70% presented the best balance.

277 For the off-centered defect position, the tested disk is shown in Fig. 7a. Iteratively estimated
278 trajectories are shown in Fig. 7b, and there is a convergence towards the result. The images
279 obtained are presented in Fig. 7c for the reconstruction using the proposed method and in Fig. 7d
280 using the FBP method. As for the centered defect case, the E_R image presented a more
281 contrasted defect region compared to the smooth variation obtained with the FBP image. Fig. 7e
282 and 7f present a vertical profile for each reconstruction, with a better-defined defect boundary for
283 the E_R image.

284 Fig. 8 presents the segmented images for the off-centered case. For the E_R image, the mean
285 value was 1250 MPa ($\sigma=812$ MPa), and for the FBP image, the mean velocity was 1330 m/s
286 ($\sigma=251$ m/s). Using the threshold value of 30% for the FBP image, defective pixels were not
287 detected. For the other threshold values, the true-positive rates were 7%, 62%, and 91% and the
288 respective false-positive rates were 5%, 9%, and 21%. For the E_R images, true-positive rates
289 were improved compared to the FBP results, with values of 73%, 84%, 94%, and 95% as the
290 threshold increased, and false-positive rates of 3%, 7%, 26%, and 50% respectively.
291 Segmentation using the E_R image and a 50% threshold led to the best compromise. Compared to
292 the centered defect case, here we obtained higher false-positive rate values. It has been shown
293 that off-centered defects resulted in lower TOF variations compared to the centric defect cases,
294 leading to less contrasted regions in the tomographic images compared to centric cases, which
295 increases the difficulty in identifying defect location (Espinosa et al. 2019a).

296

297 **4. Discussion**

298 The evaluation process of standing trees, especially in an urban context, involves subjective
299 assessments of various parameters to be measured in decay detection and loss of resistance
300 from external signs. However, the use of tools such as tomography in this process provides
301 greater support and the ability to have detailed and accurate information about the internal state
302 of standing trees. This allows making better decisions based on a deeper understanding of risk
303 factors for failure in trees. The proposed method may facilitate the interpretation of the results and
304 increase the accuracy of the extension and location of decomposition, avoid invasive tests and
305 enable timely intervention of health affectations of trees in the technical evaluation in accident
306 prevention and silvicultural management of trees. In this study, we tried to design the
307 reconstruction methodology taking into account the following criteria: a fast computing time with

308 a common computer, a low number of sensors used in-situ, and the possibility to implement the
309 proposed method in the existing commercial devices.

310 The common reconstruction techniques for acoustic or ultrasonic imaging of standing trees are
311 based on the hypothesis of quasi-isotropic behavior in the cross-section. The propagation velocity
312 of waves is supposed to be independent of the angle of propagation between the direction vector
313 and the radial axis; it is thus possible to construct an image representing a velocity value for each
314 pixel of the image. However, the hypothesis of quasi-isotropic behavior is not true, and it was
315 proposed in this study a theoretical method allowing computing a specific elastic constant for each
316 pixel. The specific elastic constant can be the Young's modulus in the radial direction, in the
317 tangential direction or the shear modulus, divided by the density. The Poisson's coefficient was
318 set to a constant ($\nu_{RT} = 0.3$) to improve the convergence of the algorithm. Furthermore, it was
319 chosen to present the results with the radial modulus of elasticity and a constant value of the
320 density equal 661 kg/m^3 (Ross 2010). To compute more precise values of elastic properties using
321 the proposed method, it would be necessary to determine the variation of the density within the
322 cross-section of the tree using another non-destructive technique than elastic waves propagation
323 analysis.

324 The sinogram was interpolated to virtually add sensors and increase image resolution while
325 limiting the number of sensors really used (which allows reducing the in-situ time inspection). A
326 sinogram grouped the set of experimental times-of-flight obtained for all the emitters (projections)
327 in a matrix form (the rows corresponded to the emitters and the columns to the receivers).
328 Assuming that the number of emitters used was sufficient to detect the presence of a defect and
329 that the physical quantity measured (time-of-flight) was continuous between two sensors, it was
330 thus possible to determine this quantity for a virtual sensor placed between two real adjacent
331 sensors by interpolation. In this case, it was chosen to use a linear interpolation procedure and
332 the number of sensors was duplicated, passing from 16 to 32 sensors. The final number of
333 sensors (interpolated sinogram) was only limited by the computing time. Interpolate the sinogram
334 allowed to obtain more accurate results than interpolating the reconstructed image because the
335 final image includes additional errors from the reconstruction process.

336 It was previously shown that the presence of bark significantly contributed to signal attenuation
337 (Brancheriau et al. 2012). Furthermore, the irregularity of the bark induces a problem of coupling
338 between the ultrasonic sensor and the wood. In this study, it was decided to remove the bark
339 because the aim was to validate experimentally the reconstruction method of the inner part of a
340 tree. For in-situ ultrasonic testing, it would be necessary to adapt or to design specific sensors

341 that optimize the coupling with the wood. A possibility would be to screw the sensor into the wood
342 through the bark.

343 The experimental tests were performed on green wood with an average moisture content of 92%.
344 The protocol was notably designed to avoid wood drying, and the time between the tree harvesting
345 and the end of the ultrasonic tests was approximatively one month. Maintaining wood above the
346 fiber saturation point allowed mimicking the state of the matter in standing tree, while having the
347 possibility to create controlled defects in the wood discs. It was reported that variation of moisture
348 content above the fiber saturation point had an impact on the propagation of ultrasonic waves in
349 wood (Sakai et al. 1990; Unterwieser and Schickhofer 2011; Yamasaki et al. 2017). The
350 harvesting and the period of storage would have softened the gradient of moisture content within
351 the wood discs, and produced a quasi-homogeneous hygroscopic state. Taking into account this
352 last hypothesis, the influence of the moisture content variation was not considered in the proposed
353 model. In addition, the internal moisture content gradient is difficult to assess experimentally
354 during in-situ field-testing on standing trees. An extension of this study would focus on the effect
355 of the internal variation of moisture content on tomographic image reconstruction and on the
356 correction of the computed characteristic parameters.

357 The proposed reconstruction method was based on the bi-dimensional hypothesis (transverse
358 cross-section of a tree). This hypothesis is encountered in all commercial tomographic devices.
359 Therefore, three-dimensional imaging is a result of the interpolation of bi-dimensional images
360 (Martinis 2004). Due to the difference of wave velocities between the longitudinal axis of a tree
361 and the transverse axes, the shape of the wavefront is more altered in the longitudinal direction.
362 The consequence is that a time-of-flight measured between two sensors placed at a given height
363 of a tree can be the result of a wave traveling with a 3D path. This is why wood discs were used
364 in this study and not tree trunks. In order to continue improving the tomographic reconstruction
365 procedure of standing trees, it would be necessary to develop a full 3D inversion technique
366 (Goncharsky et al. 2014). A full 3D setup would require a distribution of sensors at different heights
367 of a tree (not necessarily around cross-sections). The reconstruction method would consider the
368 cylindrical orthotropic condition of wood in the three directions to model the wave propagation.
369 The solution of this inverse problem does not exist up to now but would need high computing
370 capacities, as it would use a large amount of data by considering all the possible transmitter-
371 receiver combinations.

372

373 **5. Conclusions**

374 With the purpose of improving the detection of the presence of pests and diseases in standing
375 trees, an alternative procedure for the tomographic imaging of wood by elastic waves was
376 proposed. This procedure was developed for ultrasonic waves but is also valid for acoustic waves.
377 Common tomographic devices mainly use acoustic waves, and the informatics algorithms
378 developed for this work can be integrated into these commercial devices. The proposed
379 procedure gave a solution to the inverse problem of tomographic imaging by considering the
380 orthotropic behavior of the wood matter. However, the reasoning shown here can also be applied
381 for buildings structural health monitoring or medical imaging, in the case of anisotropic behaviors,
382 as examples. The orthotropic behavior of wood had the consequence that the local wave velocity
383 was not an intrinsic parameter of the matter (despite this, images of local velocities are however
384 used by common tomographic devices) because the wave velocity was a function of the
385 propagation angle between the acoustic ray and the local orthotropic axes. The proposed
386 procedure allowed determining the local values of the specific elastic parameters (Young's moduli
387 in radial or tangential direction, or shear modulus, divided by density) that are intrinsic parameters
388 of the matter, and to determine the propagation trajectories in the same computing process. It
389 mainly consisted of an iterative process focused on finding a polynomial approximation of the
390 slowness at each pixel in the image as a function of the propagation angle, modifying the curved
391 trajectories by a raytracing approach. The proposed inversion executed fast considering in-situ
392 testing. A specific interpolation procedure was implemented allowing limiting the number of
393 sensors used, which can be less time consuming for field expertise. Based on the hypothesis of
394 the continuity of the measured physical property (time-of-flight) between sensors, the sinogram
395 interpolation increased the spatial resolution of the image, which can improve the quantification
396 of the geometry and size of defects. It was demonstrated by experimental tests that the imaging
397 process led to a better defect detection compared to the use of a common imaging technique.
398 The value of the intrinsic parameter (specific modulus in radial direction) in the experimental
399 tomographic image was modified by the presence of juvenile wood and by the presence of
400 compression wood. It was thus possible to detect the compression wood by this imaging
401 procedure. Further work should consider two main research axes to obtain a better representation
402 of the tree inner state using elastic wave tomography. On one hand, the effect of the moisture
403 content above the fiber saturation point, and its variability within the cross-section of the tree, on
404 the physical parameters measured and reconstructed should be taken into account in the imaging
405 process. On the other hand, the wave propagation in the three directions of the space should be

406 considered by developing a specific experimental methodology and by developing a 3D inversion
407 procedure including orthotropy.

408

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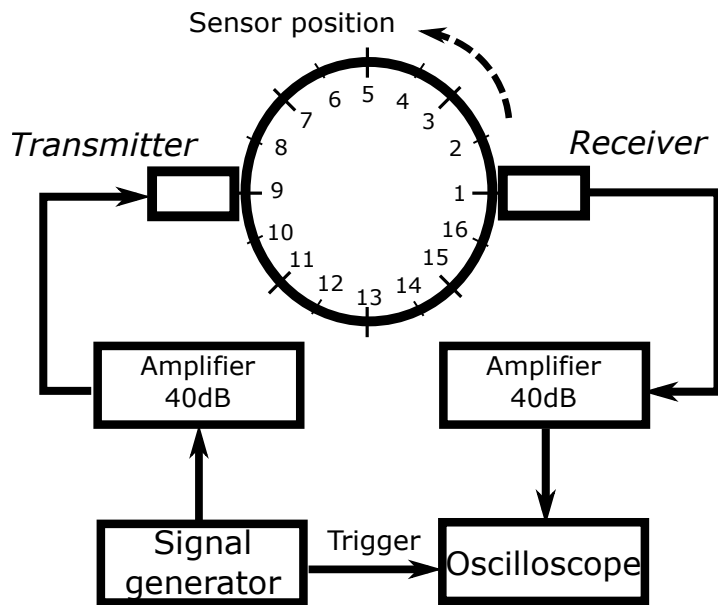
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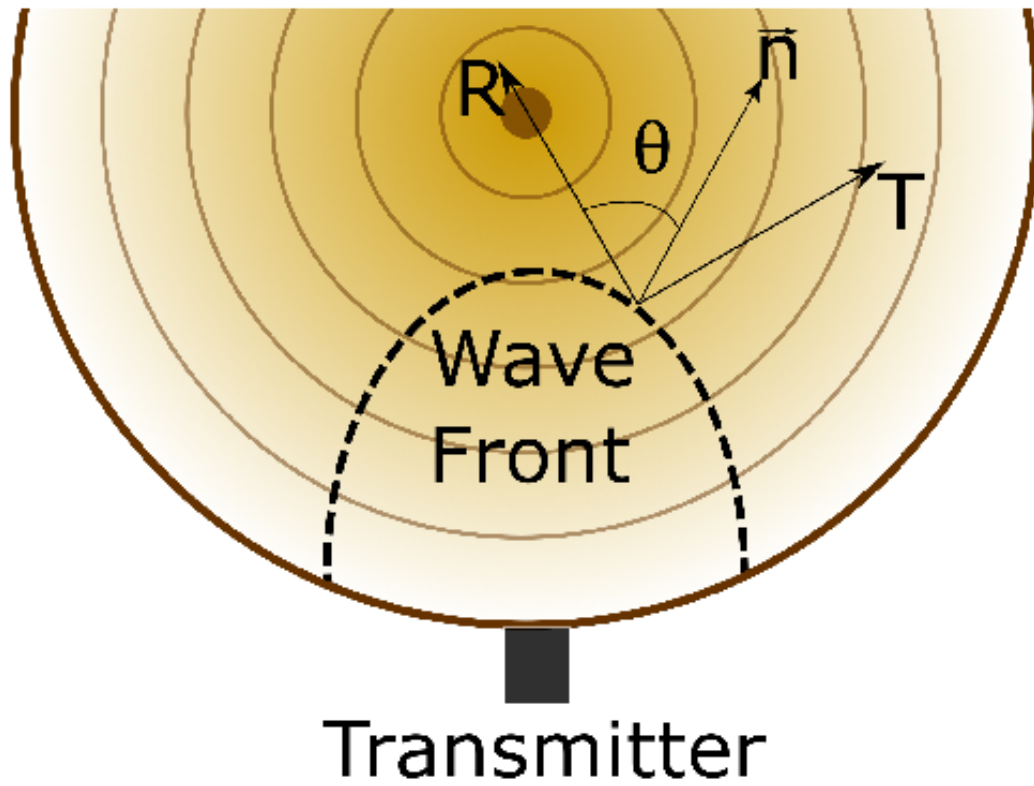
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522 **Captions of figures**



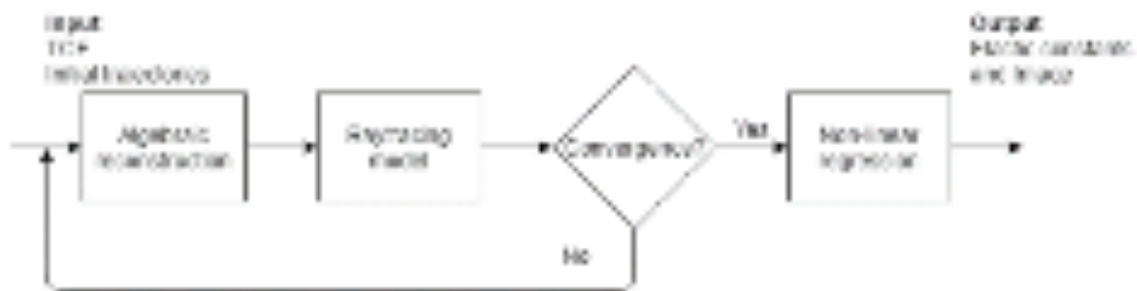
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524 **Fig. 1:** Ultrasonic chain of measurement, including the ultrasonic pair of sensors, electrical signal
525 generator and oscilloscope, with input and output amplifiers.



526

527 **Fig. 2:** Geometrical definition of θ angle and of vector n normal to the wavefront.

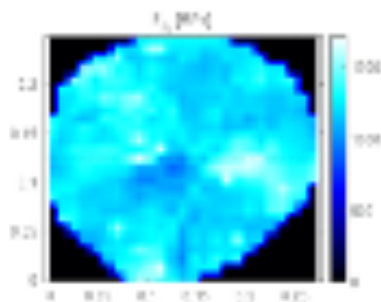


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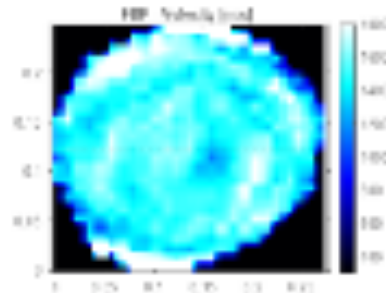
529 **Fig. 3:** Flowchart for the proposed reconstruction method presenting an iterative schema.



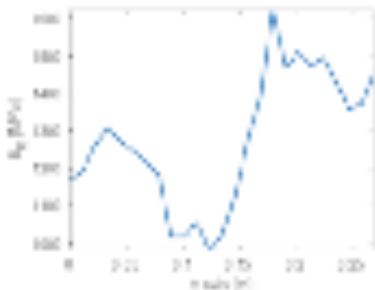
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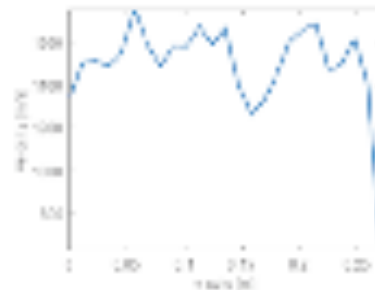
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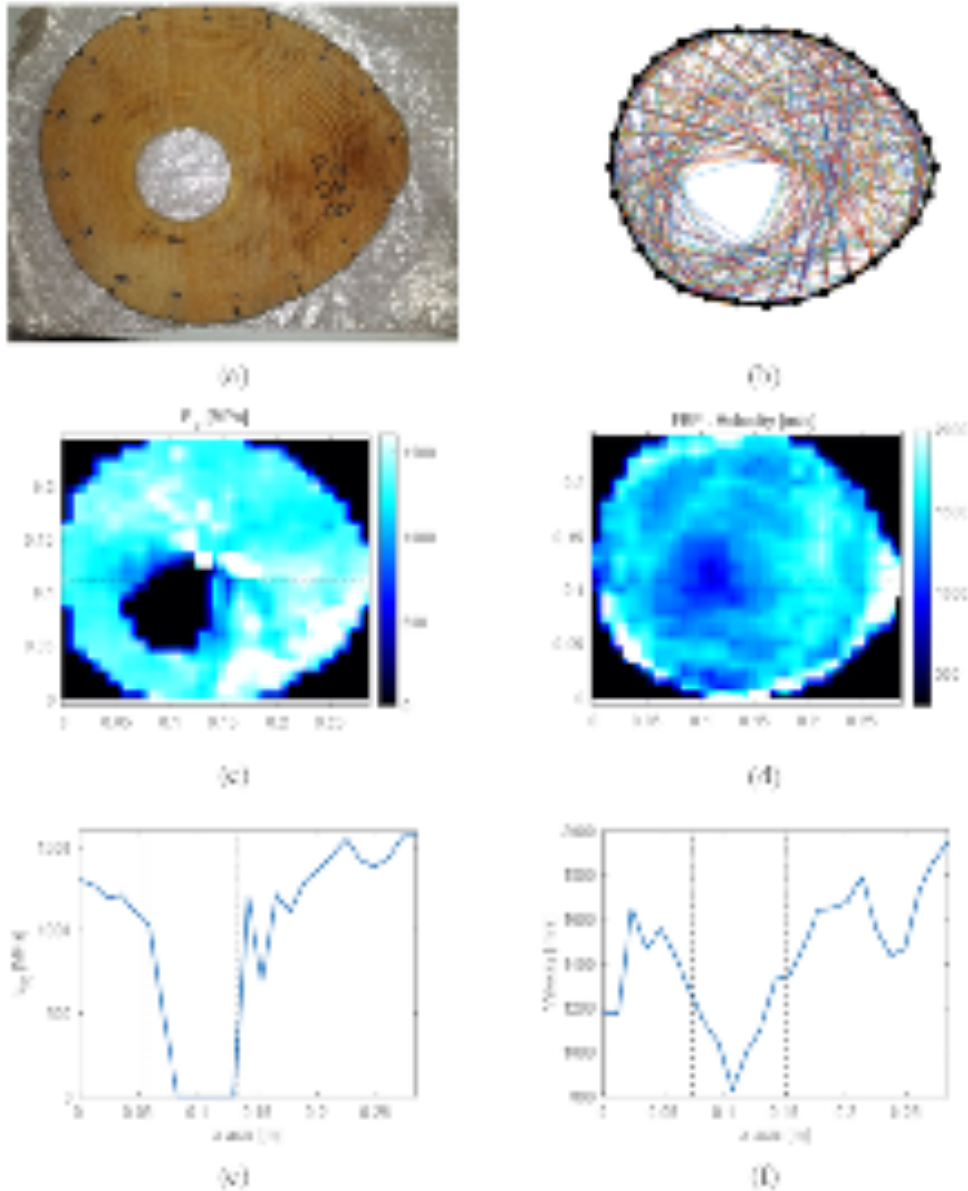
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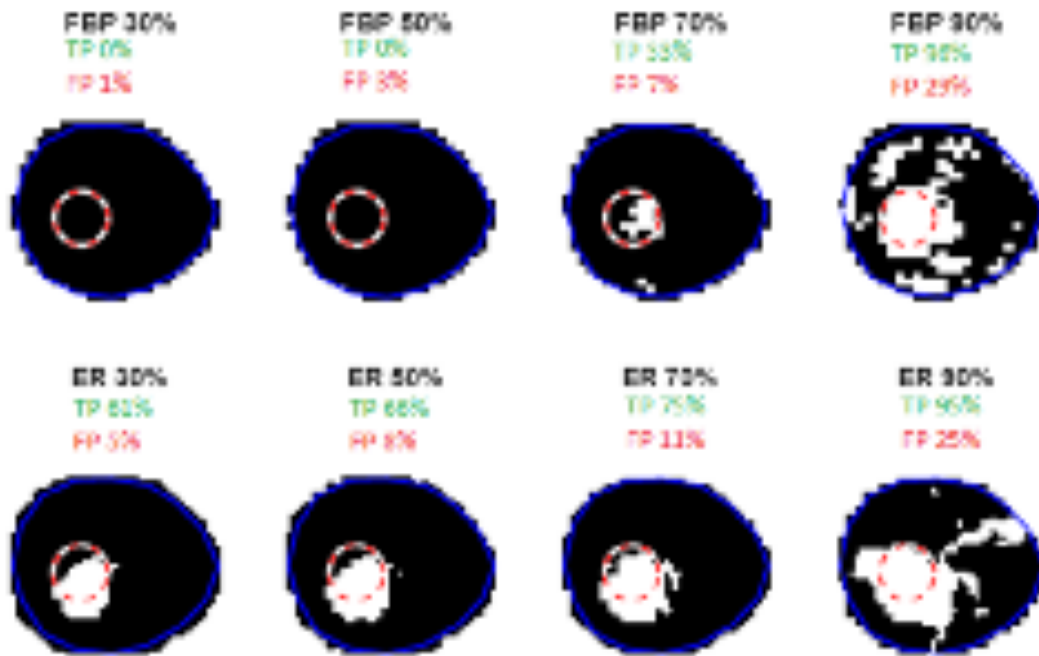
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531 **Fig. 4:** (a) Oak healthy trunk, (b) E_R image obtained with the proposed method, (c) FBP image for
 532 comparison, corresponding horizontal profiles from (d) the E_R image and (e) the FBP image. The
 533 dashed line in the (b) and (c) images indicates the profile position.



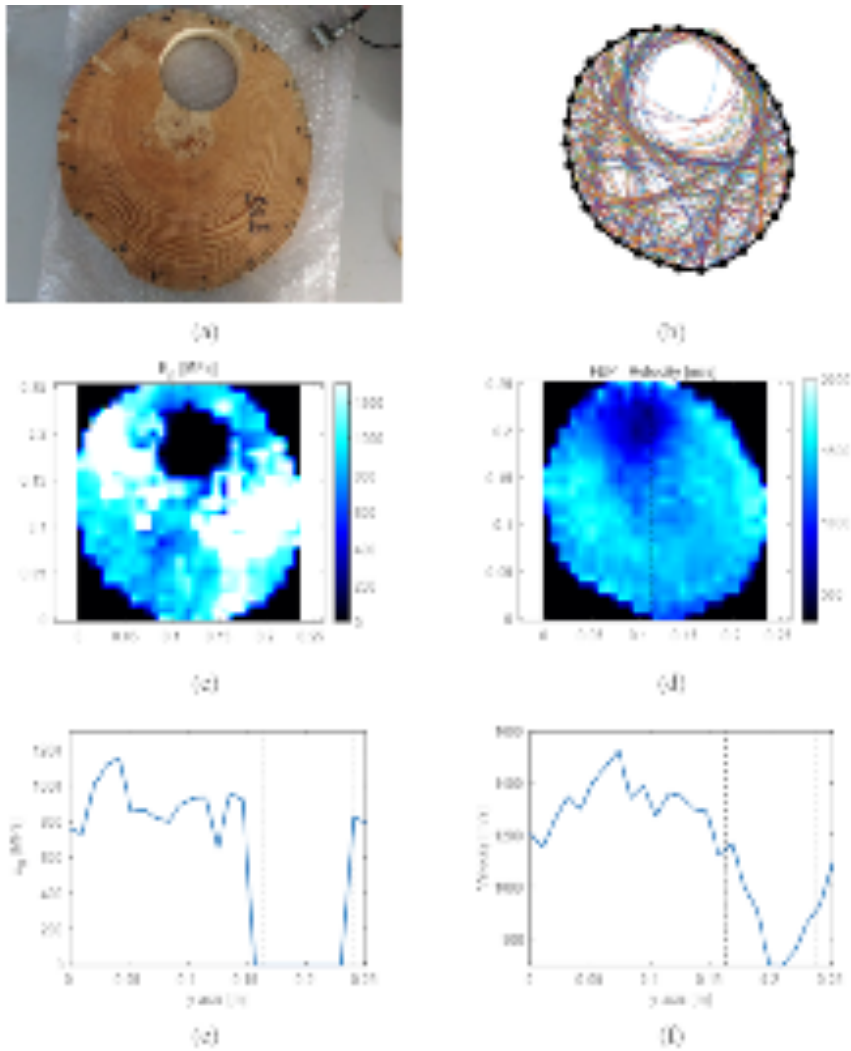
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535 **Fig. 5:** (a) Pine with a centric defect, (b) rays obtained after the reconstruction procedure, (c) E_R
 536 image obtained with the proposed method, (d) FBP image for comparison, corresponding
 537 horizontal profiles from (e) the E_R image and (f) the FBP image. The dashed line in the (c) and (d)
 538 images indicates the profile position. The dashed line in the (e) and (f) images indicates the defect
 539 position.



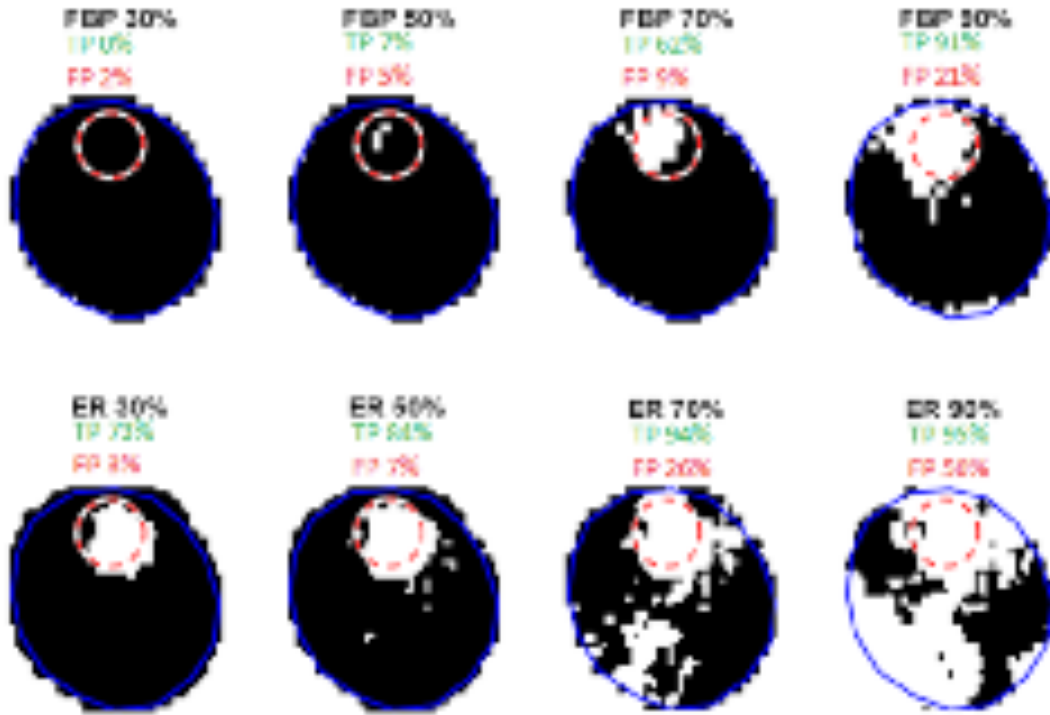
540

541 **Fig. 6:** Thresholding of the FBP images (top) and the ER images (bottom) for the centered defect
 542 case. Dashed circle represents the true geometry of the defect. White regions correspond to the
 543 pixels classified as defective.



544

545 **Fig. 7:** (a) Pine with an off-centered defect, (b) rays obtained after the reconstruction procedure,
 546 (c) E_R image obtained with the proposed method, (d) FBP image for comparison, corresponding
 547 horizontal profiles from (e) the E_R image and (f) the FBP image. The dashed line in the (c) and (d)
 548 images indicates the profile position. The dashed line in the (e) and (f) images indicates the defect
 549 position.



550

551 **Fig. 8:** Thresholding of the FBP images (top) and the E_R images (bottom) for the off-centered
 552 defect case. Dashed circle represents the true geometry of the defect. White regions correspond
 553 to the pixels classified as defective.

554

555 **Figures**