ULTRASONIC WAVE PARAMETER CHANGES DURING PROPAGATION THROUGH POPLAR AND SPRUCE REACTION WOOD

Mohammad A. Saadat-Nia,[a] Loic Brancheriau,[b*] Philippe Gallet,[b] Ali Akbar Enayati,[a] Kambiz Pourtahmasi,[a] and Farhang Honarvar[a]

Ultrasonic tests were performed in the main directions at 300 kHz in poplar and spruce reaction wood and normal wood. The experiments were conducted on 2 x 2 x 10 cm^3 specimens selected from the pith to the bark. The same phase velocity values were measured in poplar tension wood and normal wood. In compression wood, the phase velocity was lower in the longitudinal direction and higher in the transverse direction. The group velocity measured in the longitudinal direction in tension wood was greater than in normal wood, but lower values were obtained in compression wood in comparison to those obtained in normal wood. The results showed that wave attenuation cannot be significantly affected by the structural properties of reaction wood. A better wave energy transfer pathway (RMS voltage) was found in poplar and spruce reaction wood than in normal wood. Acoustic radiation in reaction wood of both species was lower than levels obtained in normal wood in all anisotropic directions. The results obtained when comparing reaction wood and normal wood of both species indicated that sound velocity decreased as moisture content increased, but the attenuation coefficients increased slightly.

Keywords: Reaction wood; Poplar; Spruce; Ultrasound; Ultrasonic velocity, Ultrasonic attenuation; Acoustic radiation; RMS voltage

*Contact information: a: Faculty of Natural Resources, University of Tehran, Department of Wood and Paper, P.O. Box 31585-4314, Karaj, Iran; b: CIRAD - PERSYST Department, Research unit: Production and Processing of Tropical Woods, TA B-40/16, 73 rue Jean-François Breton, 34398 Montpellier, France; *Corresponding author: loic.brancheriau@cirad.fr*

INTRODUCTION

Reaction wood is a natural defect in standing trees. The reason for the formation of reaction wood is mainly related to the gravitropic response, which is accompanied by hormonal stimuli. Reaction wood is compression wood in softwood species (gymnosperm wood), whereas it is tension wood in hardwood species (angiosperm wood). The anatomical and structural properties of reaction wood have been widely discussed in scientific papers (Archer 1986; Carlquist 1988). Compression wood, which is biologically optimized to improve compressive strength, is very brittle and dangerous in structural timber applications. Tension wood has a higher tensile strength and Young's modulus than normal wood. However, it also has a higher fracture toughness and impact resistance. The main problem associated with the quality and utilization of wood and timber containing reaction tissue is that their shrinkage characteristics differ from those of adjacent normal wood (Barnett and Jeronomidis 2003). So the best strategy is thus to separate this part from normal wood in order to reduce waste in wood processing. Common approaches implemented to detect the reaction zone are visual inspection (compression wood), use of the Herzberg solution (tension wood), or anatomical observation under a microscope (Badia et al. 2005).

In addition to these well known methods, non-destructive tests such as those involving ultrasound have been developed to detect reaction wood (Bucur 2003b). Ultrasonic waves are affected by the anatomical structure of wood. Thus the main descriptors of ultrasonic waves (velocity, rate of energy flow and attenuation) change during propagation. As the anatomical structure of reaction wood differs from that of normal wood, some differences may be observed in the wave descriptors. Hamm and Lam (1989) detected compression wood in green western hemlock by peaks of greatest slowness on polar graphs. Feeney (1987) observed continuously increasing velocity from pith to bark in Sitka spruce. He also found that the velocity in compression wood was less than that in normal wood. Bucur (1991) examined the ability of ultrasonic longitudinal waves to detect the presence of reaction wood in Douglas fir, pine, and beech. The use of ultrasonic tomography for detecting the presence of compression wood in spruce was also studied by Bucur (2003a). However, phase velocity was the main parameter measured in most of the studies. It is essential to analyze more parameters. Another aspect of ultrasonic behavior in wood is the effect of moisture content. Different studies were conducted on the effect of moisture content on velocity and attenuation of acoustic or ultrasonic waves (Sakai et al. 1990; Oliveira et al. 2005; Gao et al. 2009; Chan et al. 2010; Hasegawa et al. 2011). However, no references have been found concerning the effect of moisture content on reaction wood with respect to velocity and attenuation.

Because of the complexity of propagation phenomena, several parameters are required to improve reaction wood detection. The aim of this study was thus to investigate the potential of other parameters for the detection of reaction wood, such as group velocity (velocity of signal energy; Chang et al. 2006), acoustic radiation coefficient (phase velocity divided by density; Schelleng 1982; Bucur and Sarem 1992) and attenuation coefficient (absorption and scattering of waves; Rose, 2004). Conventional parameters were also used, e.g. root mean square voltage (temporal energy; Beal 2002) and the phase velocity (associated with the time of flight measurement; Beal 2002; Pellerin and Ross 2002). The effect of moisture content below the fiber saturation point (12%, 6%, 0%) was also studied relative to the wave parameters for reaction wood.

EXPERIMENTAL

Materials

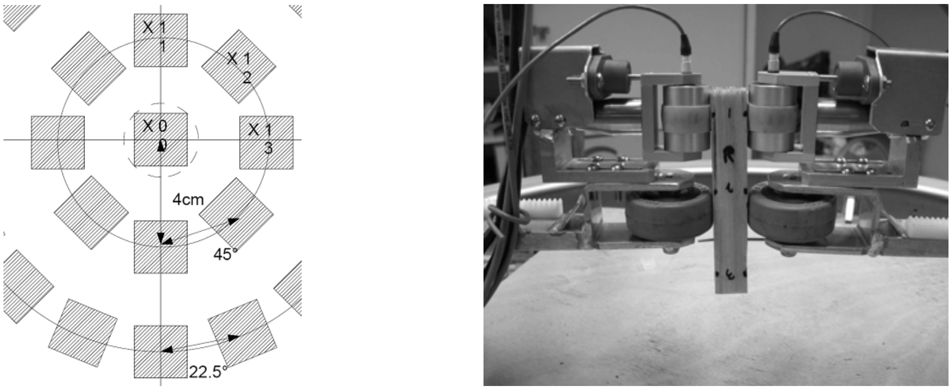
One spruce (*Picea abies*) tree and one poplar (*Populus deltoides*) tree were harvested. The trees were selected because they presented a visible asymmetric growth. Compression wood zones in spruce are easy to detect by visual observation. Poplar is known to be very sensitive to the formation of tension wood (Cunderlik et al. 1992). The sampling characteristics are presented in Table 1.

The first step was to reveal the reaction zone, which was done using the Herzberg solution for poplar and a visual inspection for spruce. The presence of reaction wood was then confirmed by microscopy experiments. 15 µm slices were cut with a microtome, washed in peroxide and ascetic acid after safranine staining and washing in different percentages of alcohol, and then the samples were ready to be analyzed under a microscope.

Table 1. Characteristics of Selected Trees

Species	Cutting area	Age (years)	Mean diameter of logs (cm)	Logs (length 1 m)	Disks (thickness 10 cm)
Picea abieas	Nancy	26	30	3	3
Populous deltoides	Montpellier	21	33	2	2

The second step was to prepare small samples for ultrasonic testing. As shown in Fig. 1, an initial pattern was designed for cutting the small samples. In this pattern, three circles were drawn at distances from the pith of 4 cm, 8 cm, and 12 cm. Then the small samples were taken from every circle (2 cm in the radial direction, 2 cm in the tangential direction, and 10 cm in the longitudinal direction). Approximately 40 samples were taken from every disk. Sometimes, due to the asymmetric shape of disks, it was not possible to sample all the positions of the external circle. In this case, the corresponding samples were taken near the pattern positions. The ratio of samples with normal wood to samples with reaction wood was 4 with the two species (at least 10 samples with reaction wood). After cutting, the samples were covered with plastic to prevent moisture loss. The samples were stored at 4 °C between each ultrasonic measurement. The measurements were done at a theoretical moisture content of 12% (20°C and 65% relative humidity). Another conditioning step was carried out to obtain a theoretical moisture content of 6% and finally 0%. In order to measure the anatomical features of reaction wood and normal wood (fiber and tracheid length, wall thickness), narrow strips (1 cm) were cut from small cubic samples (1 cm × 1 cm × 1 cm) randomly selected in every circle. Then Franklin's method (Franklin 1945) was used for fiber and tracheid suspended sample preparation. A calibrated microscope was used to assess fiber and tracheid length and also wall thickness. To calculate the real density, samples were weighed at 12%, 6%, and 0% moisture content, and then their dimensions were accurately measured.



(a) (b)

Fig. 1. Pattern for cutting cubic samples (a), ultrasonic measurement system (b)

Methods

A specific device designed at CIRAD was used for measuring wave parameters by a direct contact technique (Fig. 1, BIOGMID research project; Brancheriau et al. 2009). The ultrasonic probes had a frequency bandwidth centered on 300 kHz. The associated wavelength was 5 mm for transverse testing and 15 mm along the longitudinal axis. The probe consisted of a wheel in which the emitter was placed. The coupling medium was made with an elastomer surrounding the wheel. The emission was a square impulse of a 500V magnitude. The received signal was acquired with a converter at 16 bit resolution. The sampling frequency was set at 2.5 MHz, and the acquisition time was set at 410 µs in this specific case. In longitudinal, radial and tangential directions, signals were recorded three times for every sample. Scilab software (http://www.scilab.org/) was used for signal processing and parameters computation.

The ultrasonic signal was first filtered by a Morlet wavelet (centered frequency 300 kHz, 150 kHz bandwidth at 3 dB in order to keep a sufficient time resolution). The analytic signal was then computed to determine the temporal amplitude envelope. The time of flight (phase delay) τ_φ was defined as the first time above the background noise threshold. Thus the phase velocity V_φ was computed using the distance between the emitter and receiver:

$$V_\varphi = \frac{\text{distance}}{\tau_\varphi} \tag{1}$$

The acoustic radiation coefficient was determined using the phase velocity value as follows, with ρ being the density:

$$A_R = \frac{V_\varphi}{\rho} \tag{2}$$

The RMS voltage was computed as follows, with S_A representing the analytic signal, τ_φ the phase delay and τ_∞ the last time above the background noise threshold:

$$\text{RMS voltage} = \sqrt{\frac{1}{\tau_\infty - \tau_\varphi}\int \left|S_A(t)\right|^2 dt} \tag{3}$$

The group delay was estimated by the time associated with the maximum amplitude of the envelope. This determination was an approximation of the time associated with the maximum inter-correlation between the emission signal and the transmitted signal (considering a constant group delay in a narrow frequency band, this is the same as applying the conventional equation $\tau_g = -d\phi / d\omega$, where τ_g is the group delay, ϕ the impulse response phase, and ω the pulsation). The group velocity V_g (energy flow velocity) was computed as follows:

$$V_g = \frac{\text{distance}}{\tau_g} \tag{4}$$

The attenuation coefficient was computed via the logarithm decrement determination of the received signal, assuming that the envelope was of the form: $\left|s_A(t)\right| = A_{\max} \exp[-\left(t-\tau_g\right)/\tau_{Att}]$, with S_A being the analytic signal and τ_{Att} the characteristic time of the decrement. This led directly to the following formula, with V_φ being the phase velocity set at 1400 m/s. The phase velocity was considered constant to avoid a correlation between the two parameters *Att*(dB/m) and V_φ only due to their particular computation.

$$\text{Att(dB/m)} = 20\log_{10}\left(\frac{\left|s_A(t \equiv 1\,\text{meter})\right|}{\left|s_A(\tau_g)\right|}\right) = -\frac{8.7}{\tau_{Att}.V_\varphi} \tag{5}$$

The phase velocity, group velocity, acoustic radiation, attenuation coefficient, and RMS voltage were calculated in the main directions in reaction wood and normal wood the two studied species (Figs. 2 and 3). The standard uncertainties of the mean parameters (τ_φ, τ_g, τ_{Att}) computed with three measured values were: 0.43 µs (3%), 4.67 µs (14%), 3.61 µs (6%) in the R axis; 0.77 µs (4%), 4.38 (11%), 3.37 µs (6%) in the T axis; 0.66 µs (3%), 5.27 µs (10%), 2.69 µs (4%) in the L axis.

A factorial analysis of variance with fixed effects was used for statistical analysis. This procedure computed general linear models (GLM) that encompassed both analysis of variance (ANOVA) and regression. The estimated marginal means (least squares means) were computed to deal with the problem of unequal sample sizes.

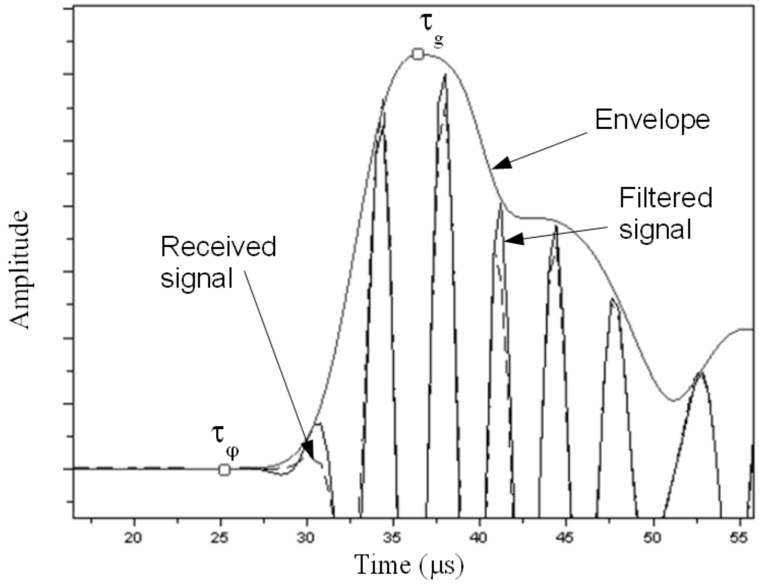


Fig. 2. Phase delay and group delay computed to determine the phase and group velocity

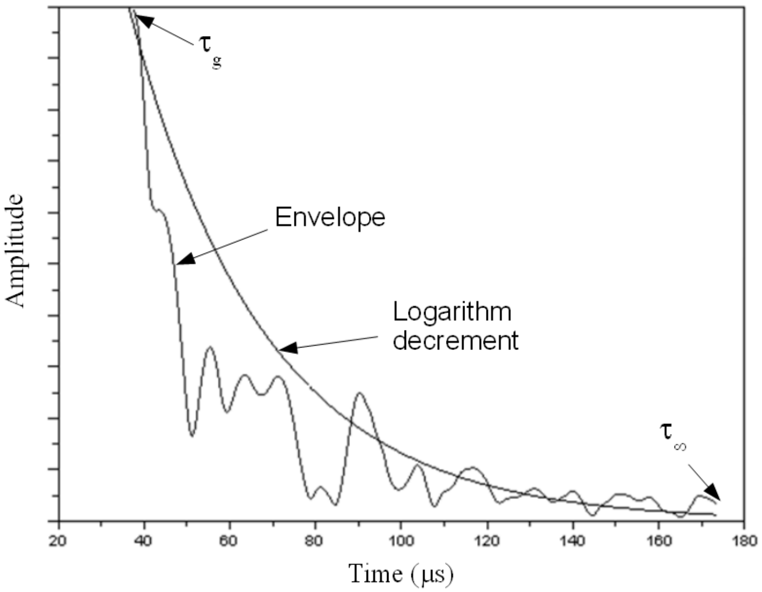


Fig. 3. Logarithm decrement determination of the received signal for computing the attenuation

RESULTS AND DISCUSSION

Table 2 displays the mean phase and group velocity values (means calculated for all samples and disks) in normal wood and reaction wood for the two species (poplar and spruce). The results show that there was no significant difference between phase velocities in poplar normal wood and tension wood in the same ring and in all the main directions (longitudinal, radial, and tangential). However, in spruce, lower phase velocity values were measured in the longitudinal direction in compression wood than in normal wood. In contrast, the phase velocity was higher in the tangential direction in compression wood than in normal wood. The lower group velocity values in compression wood and higher values in tension wood could be explained by the physical and anatomical properties of reaction wood (Table 3). These key traits are known and have been more extensively discussed by Kollman and Côté (1968) and Barnett and Jeronimidis (2003). The continuous wave path could be provided by longer tracheids and fibers in the longitudinal direction. Lower phase and group velocity values were obtained in compression wood with shorter tracheids as compared to normal wood, in agreement with the findings of Feeney (1987) and Bucur (1991; 2006). The flatter microfibril angle in compression wood could likely be helpful for wave propagation guidance in the transverse direction. The higher group velocity values in tension wood could be related to the longer fibers and to the existence of G-layer. Bucur (1991) reported higher sound velocity values in beech tension wood. In reaction wood and normal wood of two species, wave velocity variations were greater in the longitudinal direction than in the transverse direction. Another point which should be mentioned is that compression wood samples with higher density (47%) exhibited lower velocity values. A high density in compression wood was linked to a low wave velocity (Bucur and Chivers 1991; Hasegawa et al. 2011).

Table 2. Mean Phase and Group Velocities (m/s) Measured in Small Reaction Wood and Normal Wood Samples in the Three Anisotropic Directions
(L: longitudinal axis, R: radial axis, T: tangential)

Species	**Phase velocity (m/s)**			**Group velocity (m/s)**		
	V_L	**V_R**	**V_T**	**V_L**	**V_R**	**V_T**
Poplar						
Normal wood	3812° (31)	1482° (32)	919° (33)	1782** (25)	552° (26)	478° (26)
Tension wood	3730 (51)	1476 (48)	900 (55)	1912 (41)	539 (39)	484 (45)
Spruce						
Normal wood	4085** (23)	1366° (23)	870** (22)	1855* (22)	609° (19)	445° (20)
Compression wood	3305 (65)	1381 (58)	1200 (59)	1723 (55)	535 (51)	530 (52)

() Standard error of the mean
** significant at 1%
* significant at 5%
° no significant difference

Table 3. Density and Anatomical Properties of Spruce and Poplar Normal Wood and Reaction Wood

Species	**Density (kg/m^3)**	**Longitudinal elements (mm)**	**Wall thickness (µm)**
Poplar			
Normal wood	402 (33)	1.14 (0.13)	4.63 (1.61)
Tension wood	438 (26)	1.36 (0.18)	4.75 (1.53)
Spruce			
Normal wood	385 (25)	3.06 (0.60)	6.01 (2.14)
Compression wood	553 (58)	2.65 (0.52)	6.85 (2.04)

() Standard deviation

Table 4 shows the mean attenuation coefficients (dB/m) and inverse RMS voltages (V^{-1}) as an index of attenuation in normal and reaction wood (means calculated for all samples and disks). The results showed that the attenuation coefficients were not significantly influenced by the structural properties of tension wood and compression wood. No statistical differences were found for attenuation coefficients when comparing reaction wood and normal wood of both species, except in the tangential direction of compression wood. In fact, as wave attenuations can be affected by numerous factors in wood (Bucur & Bohnke 1994), this parameter was not strongly linked with the structure of reaction wood. The given result was sustained when the inverse RMS voltages were used to highlight wave attenuation in reaction wood. It seems that the higher density in compression wood could not significantly affect the attenuation of ultrasonic waves (Beal 2002). Conversely, Kawamoto (2010) reported lower attenuation coefficients in samples with higher density.

Table 4. Mean Attenuation Coefficients (in dB/m and V^{-1}) in Poplar and Spruce Reaction Wood and Normal Wood
(L: longitudinal axis, R: radial axis, T: tangential)

Species	**Att. coefficient (dB/m)**			**Inverse RMS voltage (V^{-1})**		
	Att_L	**Att_R**	**Att_T**	**a_L**	**a_R**	**a_T**
Poplar						
Normal wood	109° (15)	212° (18)	245° (19)	*2.55°* *(0.45)*	4.30° (0.46)	4.40° (0.48)
Tension wood	74 (23)	217 (25)	313 (29)	*2.34* *(0.73)*	4.31 (0.74)	5.67 (0.81)
Spruce						
Normal wood	134° (10)	249° (11)	387** (10)	*2.74°* *(0.55)*	5.02° (0.55)	7.37** (0.55)
Compression wood	98 (26)	248 (30)	178 (28)	*2.51* *(1.33)*	2.78 (1.72)	3.53 (1.47)

() Standard error of the mean
** significant at 1%
* significant at 5%
° no significant difference
Italic inverse RMS_L values indicate corrected values from 10 cm to an equivalent for 2 cm.

The mean acoustic radiation ($m^4.kg^{-1}.s^{-1}$) and RMS voltage (V) values in normal and reaction wood are shown in Table 5 (means calculated for all samples and disks). The acoustical quality of reaction wood as compared to normal wood was quantified by acoustic radiation. The findings showed that acoustic radiation was clearly lower in tension wood and compression wood in the longitudinal and radial directions. This parameter was more sensitive to the reaction wood structure than phase velocity because of the importance of the density factor in its computation. These values were not significant in tangential directions. It seems that the decreased acoustic radiation in reaction wood was mainly due to the higher density in tension wood and compression wood of both species. Schwarz et al. (2008) reported that higher density samples intensively diminished the resonance frequency and acoustic radiation in Norway spruce. The RMS voltages indicated that reaction woods with higher stiffness parameters could provide better energy flux transfer pathways in comparison to normal wood.

Variations in longitudinal phase velocity (m/s) and the corresponding attenuation (dB/m) with the moisture content (%) are displayed in Figs. 4 and 5. As noted in poplar and spruce reaction wood and normal wood, the ultrasonic phase velocity decreased while the moisture content increased, whereas the attenuation partially increased with increasing moisture content from 0% to 12%. The regression equations obtained between phase velocity and moisture content (0% to 12%) were $y = -202x + 4871$ ($R^2 = 0.99$) and $y = -132x + 3887$ ($R^2 = 0.66$) for spruce normal wood and compression wood, respectively. The regression equations between the attenuation coefficient and the moisture content were $y = 6x + 125$ ($R^2 = 0.41$) and $y = 2.5x + 94$ ($R^2 = 0.12$) for spruce normal wood and compression wood, respectively. Furthermore, the highest coefficients of determination were found between the phase velocity and the moisture content in poplar normal wood (y = -181x + 4309; R^2= 0.85) and tension wood (y = -161x + 4215; R^2= 0.93), while the regression equations between attenuation and moisture content were y = 5.8x + 94; R^2= 0.24 and y = 5.7x + 57; R^2= 0.72 for poplar normal wood and tension wood. It seems that the effect of moisture content on phase velocity was greater than on wave attenuation.

Table 5. Mean Acoustic Radiation ($m^4.kg^{-1}.s^{-1}$) and RMS voltage (V) in Poplar and Spruce Reaction Wood and Normal Wood
(L: longitudinal axis, R: radial axis, T: tangential)

Species	**Acoustic radiation (kg.m^4/s)**			**RMS voltage (V)**		
	L	**R**	**T**	**L**	**R**	**T**
Poplar						
Normal wood	9.80**	3.70°	2.29°	*0.392***	0.269°	0.262°
	(0.10)	(0.09)	(0.10)	(0.009)	(0.009)	(0.01)
Tension wood	8.86	3.40	2.02	*0.427*	0.244	0.205
	(0.16)	(0.14)	(0.16)	(0.01)	(0.01)	(0.01)
Spruce						
Normal wood	11.20**	3.77**	2.37°	*0.365**	0.231**	0.156**
	(0.06)	(0.06)	(0.06)	(0.01)	(0.006)	(0.006)
Compression wood	8.65	2.44	2.12	*0.398*	0.404	0.322
	(0.70)	(0.17)	(0.17)	(0.01)	(0.02)	(0.01)

() Standard error of the mean
** significant at 1%
* significant at 5%
° no significant difference
Italic RMS_L values indicate corrected values from 10 cm to an equivalent for 2 cm.

Below the fiber saturation point, an increase of moisture content causes a reduction in cell wall elastic constants and consequently the phase velocity decreases (Sandoz 1993; Beal 2002; Oliveira et al. 2005; Hasegawa et al. 2011). The maximum phase velocity and the minimum attenuation were measured under completely dried conditions. According to Sakai (1990), attenuation does not change from the dry state to the moisture content at which free water begins to enter the vacant space of wood cells, but then it rapidly increases. Changes in ultrasonic parameters due to moisture content variations below the fiber saturation point exhibited the same trend between poplar and spruce reaction wood and normal wood (Figs. 4 and 5).

The anisotropy of poplar and spruce expressed by the velocity to attenuation ratio is given in Table 6 for both reaction wood and normal wood. This approach to estimating wood anisotropy was proposed by Bucur (2006), and considering normal wood ratios, the values obtained here agree closely with those in the cited article. In poplar, the anisotropy of velocities in different symmetry directions was not significant between tension wood and normal wood. However, the velocity ratio in compression wood was less than that in normal wood.

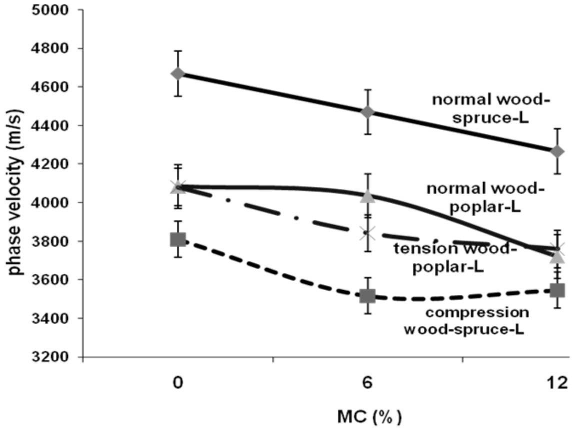


Fig. 4. Ultrasonic phase velocity in longitudinal direction (V_L) versus moisture content under the fiber saturation point in poplar and spruce reaction wood and normal wood

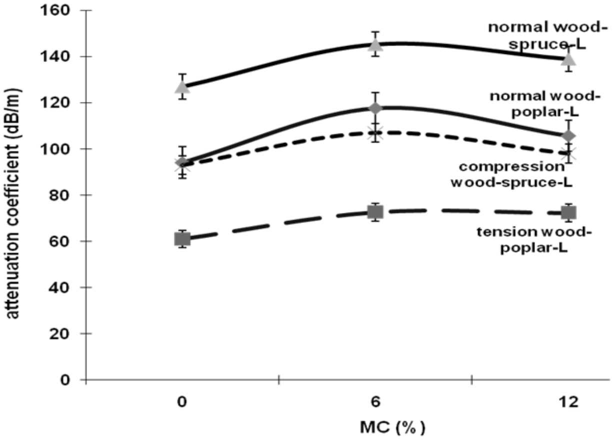


Fig. 5. Attenuation coefficients in longitudinal direction (Att_L) versus moisture content under the fiber saturation point in poplar and spruce reaction wood and normal wood

The lower anisotropy in compression wood was probably related to its higher density. This latter observation was particularly true for the V_L/V_T ratio, which could be explained by the difference in microfibril orientation (much higher than in normal wood, according to Barnett and Jeronimidis 2003). The attenuation ratios (Att_L/Att_T) in poplar were lower in tension wood than normal wood. The inverse trend is shown in Table 6 concerning spruce normal wood and compression wood. In compression wood, tracheids are more round and thick (intercellular spaces and splits in the cell wall, which might develop during the samples preparation, are also present), and they are shorter in length. In poplar tension wood, the fibers are also more round and thick, but the main key trait is the presence of a thick gelatinous layer inside, instead of an S3 layer, which is partially attached to the S2 layer (G layer has a microfibril angle close to 5°). Considering the results shown in Tables 4 and 6, the difference in attenuation between tension wood and compression wood could be explained by the presence of intercellular spaces and splits in the cell wall for compression wood, which cause dispersion phenomena.

Table 6. Acoustic Anisotropy of Poplar and Spruce Expressed by the Ratio of Different Parameters in Normal Wood and Reaction Wood

Acoustic parameter		**Poplar**		**Spruce**	
	Ratio	**N**	**T**	**N**	**C**
Phase velocity					
	V_L/V_R	2.66° (0.21)	2.66 (0.21)	3.00** (<0.01)	2.00 (<0.01)
	V_L/V_T	4.00° (0.11)	4.16 (0.11)	4.88** (0.09)	3.00 (0.17)
	V_R/V_T	2.00° (0.11)	1.83 (0.11)	2.00** (<0.01)	1.00 (<0.01)
Attenuation ratio					
	Att_L/Att_R	0.57* (0.04)	0.38 (0.04)	0.55° (0.03)	0.41 (0.06)
	Att_L/Att_T	0.41° (0.07)	0.37 (0.07)	0.34** (0.02)	0.55 (0.04)
	Att_R/Att_T	0.76° (0.16)	0.94 (0.07)	0.64** (0.10)	1.47 (0.17)

() Standard error of the mean
** significant at 1%
* significant at 5%
° no significant difference
N: normal, T: tension wood, C: compression wood.

CONCLUSIONS

Parameters derived from ultrasonic measurements were examined to investigate the ultrasonic behavior of reaction wood. Small cubic samples of 2 x 2 x 10 cm^3 in radial, tangential, and longitudinal wood directions were sampled in three disks of spruce (*Picea abies*) and two disks of poplar (*Populus deltoides*). Specific signal processing led to the determination of phase velocity, group velocity, acoustic radiation, signal attenuation, and root mean square voltage. The main conclusions are stated below:

1. The significant differences in phase and group velocity values could be closely linked with the anatomical properties of reaction wood and normal wood (Kawamot and Williams 2002). Shorter tracheids and flatter microfibril angles in compression wood and longer fibers in tension wood were the main factors affecting ultrasonic wave parameters, especially sound velocity. It seems that the higher density in compression wood and tension wood was a negative point for phase velocity, but no interaction was found between the density of reaction woods and the attenuation coefficients.
2. In reaction wood, a better wave pathway for the transfer of energy flux (RMS voltage) was noted, especially in the longitudinal direction.

3. The acoustic radiation in reaction wood of both species indicated that this parameter was more appropriate than other parameters for the detection of reaction wood in wood tissue.
4. The acoustic radiation, the phase velocity, and the RMS voltage were more sensitive to the presence of reaction wood than the attenuation coefficient. However, in comparison to the static results, underestimations could occur if phase velocity is used to measure dynamic MOE in lumber with reaction wood zones. The results suggested that the best parameter for grading poplar and spruce timbers in which there are marked density changes is acoustic radiation, since the effect of density is considered in its computation. Phase velocity is better than the attenuation coefficient for describing anisotropy in reaction wood (practically compression wood).
5. The regression equations showed that moisture content had a greater impact on the phase velocity than on the attenuation coefficient. The same trend was observed between reaction wood and normal wood of both species.

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