Detection of wetwood by ultrasonics

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Abstract

Wetwood, or bacterially infected wood, is a severe processing problem and causes serious drying defects in lumber. The detection of wetwood is, therefore, important for proper processing and quality wood products. An investigation has been carried out to detect wetwood of cherrybark oak (*Quercus pagoda* Raf.), water oak (*Quercus nigra,* L.), hickory (*Carya* spp.), and eastern cottonwood (*Populus deltoides*, Bartr. ex Marsh.) using ultrasound signals. The ultrasound measurements were carried out at different moisture contents (MCs) in three different grain directions: longitudinal (L), radial (R), and tangential (T). Each ultrasonic waveform was characterized using eight ultrasonic variables: three involving time of flight, two involving ultrasound pulse energy, one using ultrasound pulse duration, and one for peak frequency. Linear positive correlations were found for most of the time of flight (TOF) measurements with MC. A significant strong correlation was found for TOF-energy. Wetwood exhibited higher MC than healthy wood for all species and higher specific gravity for hickory. Results also showed that wetwood has a higher TOF and greater loss of energy compared to healthy wood. The grain orientation has a significant effect on ultrasound signal propagation with the lowest TOF and energy loss in the L direction. This study suggests that wetwood in living trees as well as in lumber can be identified using ultrasound-based systems.

The presence of wetwood in lumber is a severe processing problem for the lumber industry. Wetwood, which is also known as bacterially infected wood, causes serious drying defects such as excessive and deep surface checking, honeycomb, collapse, and ring separation. The wetwood-related drying defects in oak lumber alone are as much as 500 million board feet, which costs the lumber industry about $25 million per year (Murdoch 1992). The losses due to honeycomb and ring separation during kiln-drying of oak lumber are in the order of 10 to 25 percent of the dry lumber volume. In addition to the drying defects, other problems associated with machining, finishing, gluing, and odor have been reported (Murdoch 1992). Bacterial infection in living oak trees has been associated with changes in land use practices, including logging, flooding, and impeded drainage of clay soils; growth on bottomland or heavy clay soils; over maturity of the stand; and root injuries (Murdoch 1992).

Wetwood is caused by aerobic and anaerobic bacterial infection in the heartwood of living trees. It can be differentiated from healthy wood by its visibly darkened color, vinegar-like odor, higher moisture content (MC), decreased concentration of gaseous nitrogen and oxygen, higher pH, and lower electrical resistance. Bacteria in wetwood produce acetic acid and fatty acids that are often rancid and have characteristics like vinegar (Schink and Ward 1984). It is difficult to identify live trees infected with bacteria unless some external indicators such as fluxing of bacterial metabolic products occur through wounds in the bark. Wetwood has a considerable effect on the physical and mechanical properties of wood. Xu et al. (2001b) reported that wetwood has a greater MC, abnormally high radial and tangential shrinkage, and lower tension strength perpendicular to the grain for red oaks. A higher specific gravity (SG) of wetwood of western hemlock was reported by Schroeder and Kozlic (1972). Enzymes produced by the bacteria degrade hemicellulose and pectins present in the middle lamella of the cell wall, which develops abnormal checking and honeycombing in the wood.

For the last few years, several methods have been employed for detecting wetwood in living trees and lumber using stress

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wave evaluation, dielectric probes, chemical analysis, oxygen sensors, acousto-ultrasonic emission analysis, mass spectroscopy, and x-ray detection (Lawrence 1991; Murdoch 1992; Pettersen et al. 1993; Ross et al. 1994, 1995). Substantial research has been carried out for detecting wetwood in green lumber using ultrasound transmission time measurement. A strong relationship between ultrasound transmission time and wetwood showed the capability of wetwood detection using this method (Ward and Zeikus 1980, Ross et al. 1992, Verkasalo et al. 1993, Fuller et al. 1995). The measurement of transmission time is very useful when there is a significant change in physical and mechanical wood properties caused by wetwood. Wetwood that may not affect wood strength significantly but still may cause a problem in drying needs to be identified and sorted for quality wood production.

In addition to the transmission time, other ultrasonic parameters such as energy, peak amplitude, centroid time, and frequency domain energy might be helpful for detecting wetwood. The usefulness of these parameters for detecting decay and wetwood were reported by Halabe et al. (1994, 1996), Brashaw et al. (2000), and Kabir et al. (1997, 2002). This paper investigates the characterization of wetwood using ultrasound for four hardwood species: water oak, cherrybark oak, hickory spp., and eastern cottonwood.

Materials and methods

Two-inch thick discs containing wetwood and uninfected wood of water oak, hickory spp., cherrybark oak, and eastern cottonwood were collected from two different forest industry wood yards in Mississippi. The presence of wetwood was identified and confirmed by a forest pathologist based on the vinegar-like odor. A total of 60 2- by 2- by 2-inch samples were prepared from the discs, 15 (10 for wetwood and 5 for uninfected wood) for each of the species. Samples were immediately placed into cold storage to reduce drying. Ultrasound measurements were carried out at different MCs in three different grain directions: longitudinal, radial and tangential.

The ultrasound equipment we used was manufactured by the ultrasonic group of the Forest Products Division of Perceptron Inc. Details of the equipment and measurement procedures are described elsewhere (Kabir et al. 2002). Two rolling transducers were used for the measurement, one for transmitting ultrasound pulse and the other for receiving the pulse. Both transducer rollers were 9 cm in diameter and 8.9 cm in width. A plastic tier of 1.9 cm in width was mounted on each of the transducer rollers to provide good contact with the sample. Samples were placed between the transducers and data were recorded for three grain directions longitudinal (L), radial (R), and tangential (T). All measurements were carried out at 120 kHz transmitting frequency, and received signals were sampled at 500 kHz. Data were collected for eight ultrasonic variables: three for time of flight, three for pulse energy, and one each for pulse duration and peak frequency. Specifically, variables included pulse length (PL), time of flight-centroid (TOF-c), time of flight-energy (TOF-e), time of flight-amplitude (TOF-a), energy value (EV), energy/pulse value (EPV), and peak frequency (PF). Wave energy of the received signal can be expressed as the time integral of the voltage:

$$E = \int v^2(t)dt \qquad [1]$$

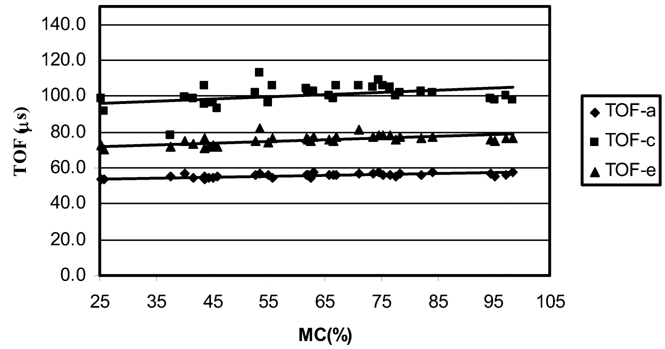

Figure 1. — Variation of TOF with MC through wetwood of cherrybark oak wood in the longitudinal direction.

The energy value (*EV*) or loss is expressed as the ratio of the energy received by the receiving transducer to the energy input by the transmitting transducer and is given by:

$$EV = 10 \log\left[\frac{E_r}{E_t}\right] - G \qquad [2]$$

where E_r = energy received by the receiving transducer; E_t = energy input by the transmitting transducer; G = receiver gain (this variable is expressed in decibel units [dB] and by convention on a logarithmic scale, hence a negative number). The TOF measurement is associated with the energy, amplitude, or centroid of the signal. The variables pulse length and energy value can be combined to provide more defect resolution capability, known as energy value/pulse.

Results and discussion

The transmission time and energy value related parameters were measured through wetwood of cherrybark oak, water oak, hickory, and cottonwood in three grain directions (L, R, and T) and at different MC levels. Data displayed in the tables and figures are for 2-inch dimension. The transmission time (TOF-a, TOF-c, and TOF-e) of cherrybark oak, water oak, hickory, and cottonwood in the green condition and L direction are presented in **Figures 1**, **2**, **3**, and **4**, respectively. To assess and quantify the effect of MC on TOF, linear regression models were developed and are presented in **Table 1** with r^2 values in parentheses. Positive correlations were found for TOF with MC for all the TOF parameters except TOF-a for hickory, where a negative correlation was exhibited. A significant strong correlation was observed for TOF-e for all the species. It is possible that the increase of free water increases the attenuation, resulting in higher TOF values. Sakai et al. (1990) and Kabir et al. (1997) also reported similar trends of TOF with MC.

Physical properties such as MC and SG of healthy and wetwood in the L direction are presented in **Table 2** with coefficients of variation (COV) in parentheses. It is evident from the table that the MC of wetwood is higher than the healthy wood for all species. The COV seems to be reasonable and cottonwood displayed a little higher COV in some cases. We collected samples randomly from different logs that varied in factors such as tree location, age, sample position within the tree, heartwood, and sapwood. This may be the reason for the higher COV for some species. Hickory was the only species where the SG changed considerably within the wetwood. There was very little or no change in the other species. Contradictory results of SG with wetwood were observed by some

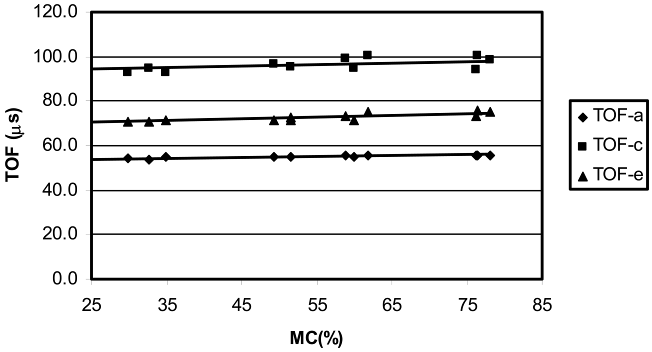

Figure 2. — Variation of TOF with MC through wetwood of water oak wood in the longitudinal direction.

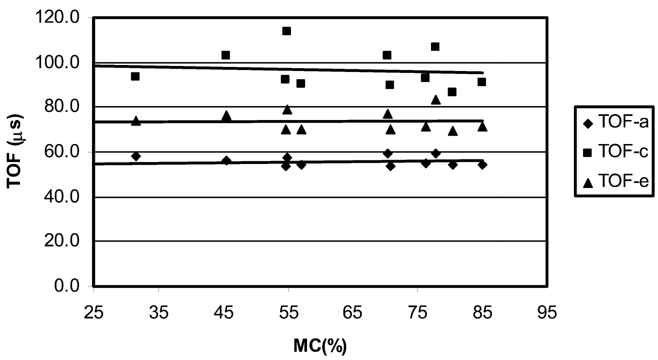

Figure 3. — Variation of TOF with MC through wetwood of hickory wood in the longitudinal direction.

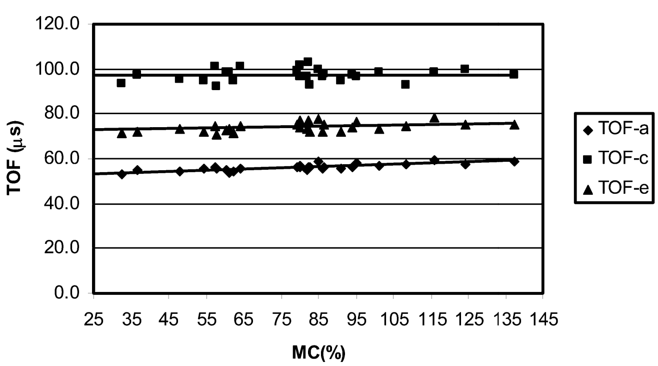

Figure 4. — Variation of TOF with MC through wetwood of cottonwood wood in the longitudinal direction.

researchers (Schroeder and Kozlik 1972, Xu et al. 2001b). Schroeder and Kozik (1972) reported a higher SG in wetwood of western hemlock than normal wood. On the contrary, Xu et al. (2001b) found lower SG in Mississippi red oak. This study also indicated an increased SG in hickory. This increase is probably related to the increased production of extractives by bacterial activities, as reported by Ward and Zeikus (1980). The wetwood does not have much effect on SG for cherrybark oak, water oak, and cottonwood (**Table 2**). The change in physical properties such as SG might be influenced by the severity of wetwood infection. A lack of change in the SG of wetwood was also observed by Xu et al. (2001) for red oak wood from South Carolina.

TOF measurements show that wetwood has a greater transmission time for all species and TOF variables (**Table 2**). This means that the infected wood is a greater impediment to ultrasound transmission compared to healthy wood. The difference in transmission time between wetwood and healthy wood is approximately 2 to 8 µs for the 2-inch dimension. The greatest difference was found for TOF-e, which can be used for identifying wetwood. The reduction of TOF through wetwood was also reported by Ross et al. (1994). The energy-related parameters such as EV and EPV of wetwood and healthy wood are presented in **Table 3**. Wetwood causes higher energy loss in the ultrasound transmission compared to healthy wood for all the species and the results are very consistent. The energy loss through wetwood of cottonwood is somewhat greater than the other species. This may be due to the greater severity of wetwood infection for this species. Brashaw et al. (2000) obtained a somewhat higher energy loss through wetwood using a similar type of instrument for red oak. The higher energy loss in wetwood may be associated with the increased viscoelastic damping and thus higher energy absorption.

The ring orientation is the most important factor that significantly influences ultrasonic transmission through wood and their attendant measurements. The results presented and discussed so far were of data measured in the L direction. The ratio of ultrasonic velocity (reciprocal of transmission time) in L, R, and T axes is roughly 1:2:3 as reported by Kabir et al. (1997) and Bucur (1988). The comparison of TOF and EV through wetwood of cherrybark oak, water oak, hickory spp., and cottonwood in three grain directions are presented in **Figures 5** and **6**, respectively. The values vary as L>R>T for both TOF and EV for all species. Cottonwood displayed larger variation among L, R, and T than the others species. Very little difference in EV was observed between R and T directions for some species. This happened because samples were not cut perfectly radially or tangentially. Higher energy loss was reported across the width (tangential) of the board than through the thickness (radial) by Brashaw et al. (2000).

Conclusions

Wetwood affects ultrasound transmission as evidenced by measurements such as transmission time and signal energy in cherrybark oak, water oak, hickory spp., and cottonwood. Positive correlations were observed between TOF and MC for

Table 1. — Relationship between MC and TOF through wetwood.

Species	TOF-a (µs) equation	TOF-c (µs) equation	TOF-e (µs) equation
Cherrybark oak	Y = 0.1254MC + 92.6	Y = 0.092MC + 69.9	Y = 0.056MC + 52.2
	(0.324)[a]	(0.625)	(0.749)*[b]
Water oak	Y = 0.65MC + 92.9	Y = 0.069MC + 69.0	Y = 0.043MC + 52.6
	(0.318)	(0.658)	(0.897)*
Hickory	Y = −0.052MC + 99.7	Y = 0.092MC + 73.2	Y = 0.030MC + 53.7
	(0.034)	(0.004)	(0.086)
Cottonwood	Y = −0.003MC + 97.5	Y = 0.024MC + 72.2	Y = 0.056MC + 51.6
	(2E-05)	(0.251)	(0.871)*

[a]Numbers in parentheses are r^2 values.
[b]* = significant at 5 percent level of probability.

Table 2. — Some physical properties and ultrasonic transmission times through wetwood and healthy wood in the longitudinal direction at green moisture content.

	MC		SG		TOF-a		TOF-c		TOF-e	
Species	W	H	W	H	W	H	W	H	W	H
	(%)				(μs)					
Cherrybark oak	86.1	67.4	0.76	0.73	59.5	56.7	101.9	76.7	82.9	76.7
	(12.8)[a]	(0.4)	(7.9)	(4.2)	(1.6)	(3.2)	(4.2)	(1.4)	(1.6)	(2.6)
Water oak	87.5	76.6	0.73	0.73	58.7	55.7	100.4	97.3	79.3	74.7
	(1.4)	(3.2)	(3.4)	(6.6)	(0.3)	(1.1)	(3.2)	(4.5)	(1.5)	(3.2)
Hickory	81.0	69.4	0.82	0.72	58.0	54.8	97.0	94.9	77.8	72.5
	(4.4)	(15.7)	(3.6)	(1.8)	(5.7)	(4.4)	(11.3)	(2.4)	(10.2)	(2.0)
Cottonwood	98.5	89.6	0.48	0.48	58.6	54.8	97.6	94.4	77.2	71.3
	(19.4)	(20.7)	(10.3)	(9.4)	(2.6)	(2.0)	(2.7)	(2.7)	(2.7)	(2.2)

[a]Numbers in parentheses are coefficients of variation.

Table 3. — Energy values and energy/pulse values through wetwood (W) and healthy wood (H) in the longitudinal direction and green condition.

	EV		EPV	
Species	W	H	W	H
	(dB)			
Cherrybark oak	−57.5	−52.9	−65.0	−59.6
	(2.6)[a]	(7.5)	(4.0)	(7.2)
Water oak	−55.4	−51.2	−62.3	−56.2
	(1.4)	(1.0)	(1.2)	(2.9)
Hickory	−60.2	−54.5	−61.8	−57.8
	(3.9)	(8.3)	(8.1)	(5.8)
Cottonwood	−54.8	−48.8	−63.2	−56.1
	(10.3)	(16.4)	(4.8)	(4.5)

[a]Numbers in parentheses are coefficients of variation.

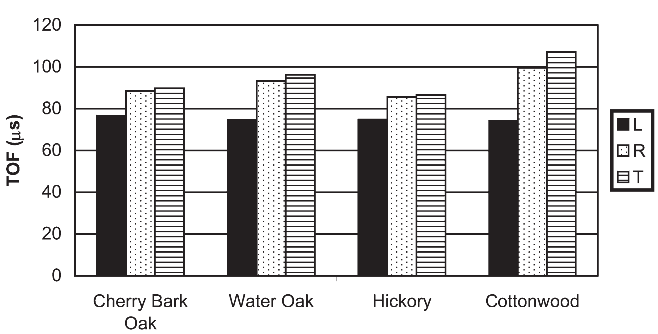

Figure 5. — Comparison of TOF in three grain directions and green condition.

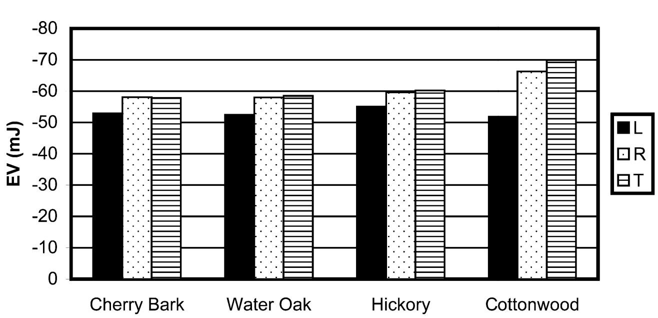

Figure 6. — Comparison of EV in three grain direction and green condition.

most of the species. Wetwood has a higher MC than healthy wood for all the species and a higher SG for hickory only. Higher SG was observed for hickory only whereas no significant differences were found for the other species. The transmission time through wetwood is greater than it is through normal wood for all species measured. The TOF-e was found to be more effective than the other TOF parameters. Wetwood showed a higher energy loss dependent upon the degree of severity. The grain orientation has considerable effect on both the TOF and energy loss variables. Ultrasound energy applied in the L direction showed the lowest TOF and energy loss, whereas ultrasound energy applied in the T direction resulted in the highest TOF and energy loss. These results open the possibility of identifying wetwood by ultrasound scanning machines in lumber or in living trees; however, it needs further investigation with other species and sample size.

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