Ultrasonic inspection and analysis techniques in green and dried lumber

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Abstract

Ultrasonic inspection of lumber has been under investigation for over 20 years, with little commercial impact. Recently, the USDA Forest Products Laboratory (FPL) developed ultrasound-based scanning technology to examine both green and dried lumber. In green lumber, the bacterial infection called wetwood (a significant source of degradation in oak at the kiln-drying stage) was found with high accuracy using time-of-flight techniques. A similar approach was used to locate checking and honeycombing in dried lumber, defects that are often not apparent by external visual inspection. This technology has been licensed and is now being developed for commercial use by the Perceptron Inc., Ultrasound Technology Group, whose specialty is ultrasonic systems and signal processing. The current phase of the project involves a flexible testbed system that can:

- accommodate a wide range of lumber specimens;
- permit automated ultrasonic inspection; and
- account for the specimen's width and thickness.

The inspection provides complete sampling of the ultrasound waveform, so several different signal-processing strategies may be examined beyond the time-of-flight approach commonly used. Special display software allows the user to plot several analysis parameters as a function of position along the length of the specimen. A set of novel signal criteria indicative of different conditions within the wood specimens has been developed. This paper describes the design of the system and its unique features, the unique analysis approach, and results obtained to date.

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Introduction

Background on needs

Hardwood lumber production in the United States is estimated to be around 10 billion board feet per year, about 50 percent of which is red and white oak (6). While the demand for domestic oak continues to grow, the quality of the raw logs continues to decline. A major factor contributing to this decline is the prevalence of a bacterial infection called wetwood, which affects up to 10 percent of the green lumber being processed (6). Wetwood is a condition resulting from the infection of living trees by anaerobic bacteria (15, 17). These bacteria secrete enzymes that degrade hemicellulose and pectic substances in the middle lamella of the cell wall (13, 17), thus weakening the chemical bonds between wood cells. Wetwood retains its original density, however, because the bacteria cannot degrade either alpha cellulose or lignin. As a result, the condition cannot reliably be detected by measuring specific gravity or moisture content.

Because of the breakdown of the middle lamella, wetwood is unable to withstand the stresses of the kiln-drying process (16), thus making it a major source of lumber degradation. It has always been difficult to kiln-dry oak, which is refractory in nature and slow to dry. When bacterially infected oak lumber is subjected to normal kiln-drying, weakened cellular bonding causes steep moisture gradients to develop within the wood. These gradients lead to abnormal splits, ring failure, surface or end checking, and separation of cell walls resulting in large internal voids not visible on the surface (honeycombing) during drying, causing total loss of utility (7). Shrinkage, collapse, and warp may also be more frequent and severe in infected wood (16). Although the problems associated with wetwood occur mostly during the drying process, other problems associated with machining, finishing, gluing, and odors may occur (5, 18).

Responding to this pressing industry need, researchers at the FPL developed an ultrasound (stress-wave) inspection technique capable of detecting both wetwood in undried and partially dried lumber, and internal defects (checking and honeycomb) in dried lumber. The FPL researchers found that wetwood causes significant changes in the propagation of sound energy across the grain of the wood (2, 3, 8–12). Thus, if ultrasound was sent across the width of a board, the nature of the signal received at the other side would provide an indication of the presence of wetwood. Specifically, the attenuation (loss of signal strength) and sound speed (rate at which the sound travels) both appear to change. Their instrumentation consisted of a commercially available "sound speed meter" (V-meter, James Instruments) and two ultrasound transducers mounted in rolling heads. This allows a board to be fed between the two rollers and scanned along its length. Their work showed a marked change in the sound speed as measured by the V-meter in the presence of wetwood (8–12). They were able to set speed-of-sound criteria for wetwood in red oak that provided good discrimination between infected and uninfected samples. They tested whether the same technique could be used to detect honeycomb and internal checking in dried lumber. They found similar, although less dramatic, changes in apparent sound speed due to internal defects (2, 3). Table 1 summarizes the data for both dried and undried lumber.

Table 1.–*Correlation between drying defects and sound transmission time in green and dried red oak lumber.*

	No. of cross sections		
Sound transmission time	Honeycomb or surface checks	No honeycomb or surface checks	Total no. of cross sections
(µsec./ft. (µsec./m))			
Green:			
>400 (>1,310)	51 (82%)	11 (18%)	62
<400 (<1,310)	117 (23%)	386 (77%)	503
Dried:			
<250 (<820)	7 (4%)	192 (96%)	199
250 to 300 (820–984)	27 (32%)	58 (68%)	85
>300 (>984)	247 (98%)	5 (2%)	252

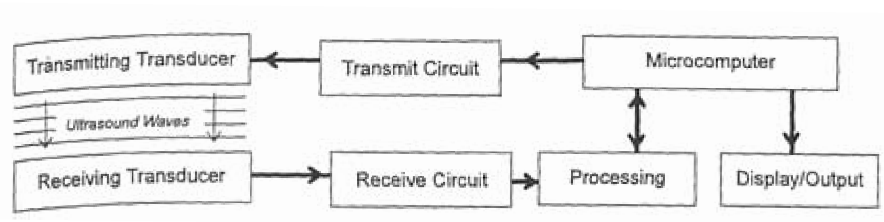

Figure 1.–*Block diagram of through-transmission ultrasound system.*

This innovative approach was patented in 1994 (8). In 1997, an exclusive license to the technology was granted in order to move it into the commercialization phase. However, in order for the FPL technology to reach commercialization, a more thorough analysis of the underlying ultrasonic system design was required. The next step was to take their proof-of-principle stage as a starting point and do a fundamental redevelopment of the ultrasound analysis techniques. The benefits of this approach include:

- the system is designed from the start to detect the specific changes in wood acoustic properties caused by wetwood and/or internal defects;
- the system accounts for the needs of industrial use, including noise and vibration, automated analysis capabilities, and board speeds up to 200 ft./min.; and
- by reexamining the detection process, the system's capabilities may be significantly extended to detect other industry needs such as knots and other smaller defects, and potentially to determine structural soundness in softwoods.

Background of ultrasonic technology

Ultrasonic imaging is used by bats and dolphins in echolocation and finding prey. Ultrasound imaging works because the different materials and fluids have slightly different structural characteristics, leading to differences in acoustical properties. Unlike most medical systems, where the information of importance is what is reflected back to the transmitter, we are interested in what travels through the object to a separate receiver (called a through-transmission system). When sound waves travel through a medium, a percentage of the sound energy is attenuated by either absorption (converting the mechanical vibration energy of the Wave into heat) or scattering (reflection of the sound into other directions than the main beam). The remaining energy can be received and processed into an indicator of the material properties between the transmitter and receiver. The device that converts electrical energy into ultrasound waves (and back again upon reception) is called the transducer. Figure 1 shows the basic parts of an automated ultrasound through-transmission system.

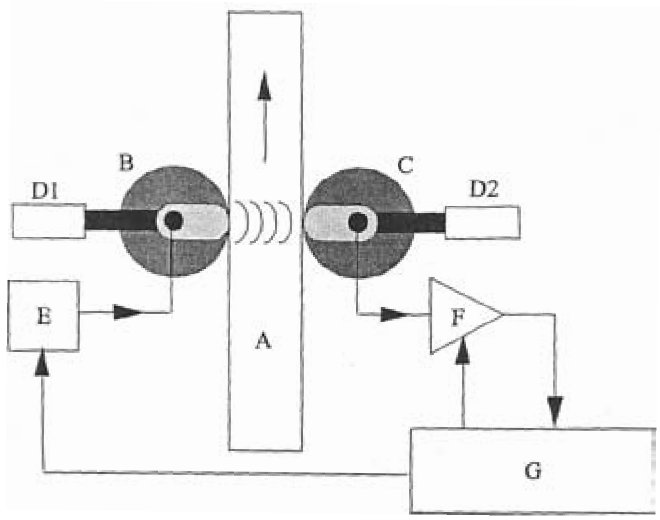

Figure 2.–*System implementation schematic.*

Two material properties that can be easily inferred are the speed of sound in the material and its attenuation properties. With this material as background, the next section describes the implementation of a through-transmission ultrasound system for lumber inspection.

System components.—Figure 2 shows a basic schematic diagram of an implementation suitable for in-plant lumber processing. A board (A) travels between the transmitting (B) and receiving (C) transducers, which are imbedded in rolling contact mounts so that the board can pass between. The transmitting electronics (E) are designed for optimal matching to the transducers, providing the best possible received signal.

The transducers are held against the board by pneumatic cylinders D1 and D2, which will accommodate a range of board widths. The receiver (F) amplifies and filters the signal from the receiving transducer (C). The received signal is sampled by a high-speed analog-to-digital converter incorporated with the controller (G), and software programmed into the controller analyzes the signal and detects the various board characteristics.

The microprocessor system (G) is designed to control the operation of and gather data from the testbed. The control involves the application of pressure to cylinders D1 and D2 at the proper time. Additional data is gathered from other sensors (not shown) including analog signals proportional to board width and height, digital signals for board length (one digital pulse every 1/8 inch along the board), and digital signals for the start and end of the board (two digital signals, one indicating the board is approaching the transducers and one indicating that the board is directly in front of the transducers).

The system is driven by a Micron Corporation 266-MHz Pentium II computer, with two data acquisition boards (National Instruments AT-MIO-16E and AT5 102) for basic analog and digital inputs and outputs, and high speed acquisition of the ultrasound signals. This approach allows for maximum flexibility and rapid system integration. An external interface module has been constructed to connect the computer system and boards with the sensors and transducers on the testbed.

System design considerations

There are several system design considerations that have been addressed during the design of the testbed, including transducer design, frequency of operation, filtering and amplification, signal detection, and overall electronic control.

Transducer design.–The transducers used were off-the-shelf units (James Instruments), and several different transducers can be accommodated by the cylinders. One task will be to examine the effects of improved transducer characteristics, which should improve defect detection. Additional transducer designs are currently under development that provide improved penetration (higher power) with better resolution (better temporal response).

System operating frequency.–Another area being examined is the effect of system operating frequency. Higher frequencies provide better resolution of small defects, but are subject to higher attenuation levels; conversely, lower frequencies penetrate through the wood more easily, but have poorer resolution. System frequency is set by the transducers used and by the transmitting electronics (E in Fig. 2.) The new system uses a controlled bipolar high-voltage pulser that can operate from 20 to 1.2 MHz, at voltages up to 850V. This provides a significantly improved signal-to-noise ratio. This computer monitors the voltage using a 100:1 voltage divider.

Filtering and amplification.–On the other side of the board, the signal from the receiving transducer (C) is amplified and filtered (Item F). The filtering reduces unwanted noise, especially vibrational interference caused by the rough edges of the board. The filter is tuned to match the transmitting frequency and transducer characteristics. The signal is amplified, with the amount of amplification adjustable over a ±40dB (1000:1 ratio) for different types of wood, board widths, and heights. This adjustment is under computer control and is tied into the signal measurement algorithms, so that changes in gain are not mistaken for differences in wood characteristics.

Signal detection and analysis.—The computer system has a high-speed data acquisition board (oscilloscope card), with a maximum sampling rate of 20 MHz at 8-bit resolution. Once in the computer, LabView™ software is used to determine the relevant signal characteristics (in addition to controlling the overall operation of the system). The principal parameters determined follow from those reported in the literature: sound speed in the material and signal attenuation. There are several approaches for estimating an attenuation value. Obviously the peak-to-peak signal level can be used, although this tends to be noisy. Several other techniques are suitable and experiments are being conducted to determine the optimal approach. The data reported later show measurements of the power ratio of the received energy to the transmitted energy as one measure of signal attenuation. Another metric is the temporal "distortion" of the pulse shape, which is indicative of wave distortion over the path from the transmitter to the receiver.

Figures 3 and 4 are photographs of the system installed at the Forest Products Laboratory. Figure 3 is the overall system (with conveyor assembly, electronics module, and computer). Figure 4 shows a close-up of the transducer and air cylinder assembly. Note the sample board in this photograph, which was specifically prepared to simulate knots.

In summary, the testbed system permits a number of different critical features of the design to be tested as the basis for further commercialization and development. It should also be made clear that the detection parameters for wetwood are expected to be fundamentally different from those used to detect honeycomb, because of the differences in sound transmission in dried and undried lumber. However, the basic system is flexible enough to accommodate both cases.

Results of preliminary studies

Although the published and patented work of the FPL has indicated that both the wetwood in the green state and checking/honeycomb in the dried state can be detected by a change in sound speed and attenuation, they have emphasized sound speed measurements in most of their work (2, 3, 8–12). Our goal is to expand the list of parameters extracted from the received signals in order to provide better overall detection accuracy and reliability, and better sensitivity for smaller defects such as knots.

We first conducted two field trials at nearby lumber facilities prior to the design of the testbed. One such test involved only honeycomb/checking; the results showed that with proper adjustment, checking could be identified by sound speed. Signal amplitude changes were also seen, even without any adjustment. At another location, both dried and undried pieces were examined. Dried lumber with clear end checks was tested, and the extent of the checking from the end was successfully determined within one inch. For undried lumber, the signal amplitude differences between "normal" and suspected wetwood were on the order of 10 to 1. From a theoretical standpoint, we surmise that wetwood causes increased viscoelastic damping (and therefore absorption), while honeycomb causes scattering (and therefore increased attenuation). The mechanisms are different, but the results are similar.

A short initial series of investigations was then conducted using the new testbed. First, a 1/2-inch-thick, 10-inch-wide piece of Lexan was used as a calibration reference. The signal through this specimen is shown in Figure 5. The signal is essentially a Gaussian-weighted sinusoidal tone burst at 75 kHz. The system gain of the signal has been adjusted to produce a signal of approximately ±1V. There is sufficient additional system gain to produce up to a ±5V signal without distortion. In Figure 6, the signal through a clear portion of an oak specimen shows nearly the

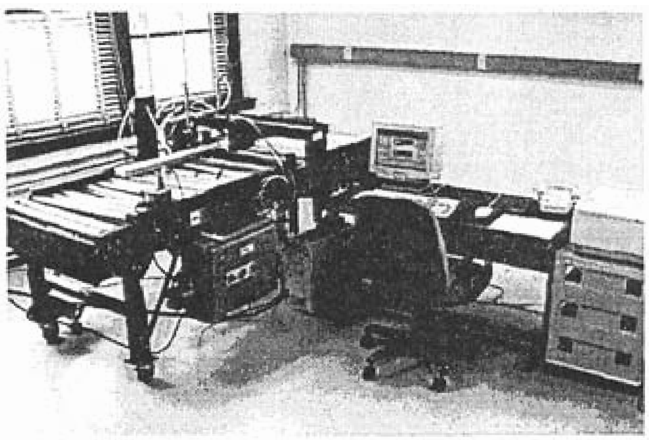

Figure 3.–*Testbed system installed at the Forest Products Laboratory.*

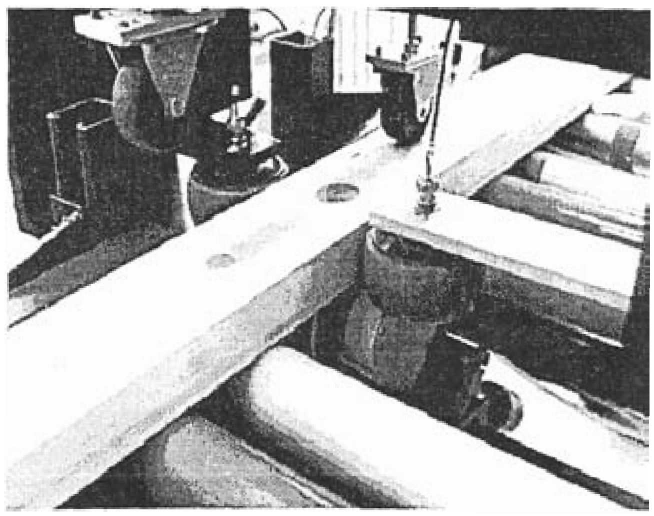

Figure 4.–*Sample board between roller transducers.*

same characteristics of the reference specimen. Figure 7 shows the signal through a section with light to moderate checking. Note the drastically reduced signal amplitude, as expected from the prior literature (2, 3, 8–12).

A further study was conducted using over 100 oak boards measured both green and after drying. Table 2 is a comparison of typical results for different wood conditions. It demonstrates the large signal variations caused by the different conditions; the larger the difference, the better the detectability of the condition.

One specific feature of the program is the ability to automatically plot the received signal characteristics as a function of position along a test board. Figure 8 shows the results from a sample board that has been prepared with a series of ironwood inserts to simulate knots (Fig. 4). The graph in Figure 8 shows both a temporal parameter and an energy parameter as a function of position. The coincidence of the two signals is indicative of the presence of knots. It is clear that there is a dramatic change in the signal in the vicinity of the defects. After the board was constructed and tested, it was discovered that there was significant internal checking at one end. This is clearly seen in the fall-off of the energy parameter.

This plot was available as soon as the board had cleared the ultrasound rollers. This type of information will be vital to the incorporation of this scanning technology in conjunction with an automated saw.

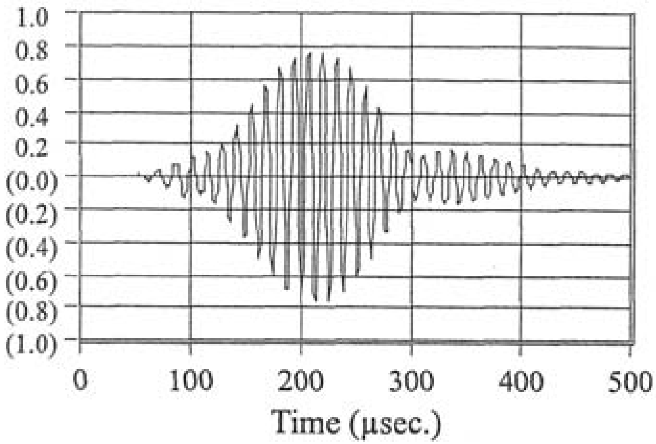

Figure 5.–*Reference time-waveform signal through Lexan.*

Table 2.–*Comparison of measured parameters for different wood conditions.*

Condition	Energy loss	Time distortion	Time of flight
	(dB)	---- (µsec.) ----	
Normal	–50	110	80
Wetwood	–70	235	90
Knot	–66	244	80
Honeycomb	–78	239	96

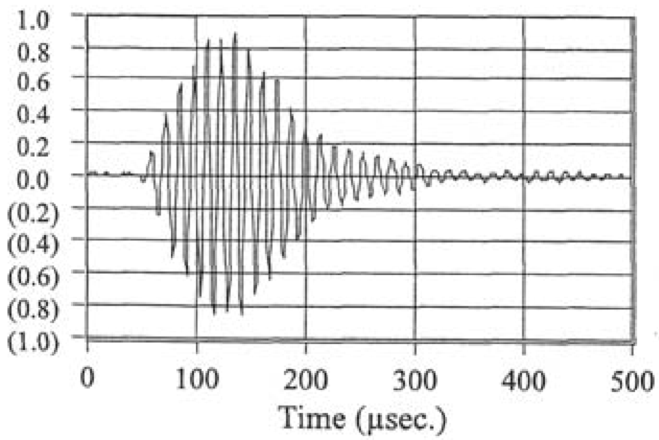

Figure 6.–*Time-waveform signal through clear section of wood.*

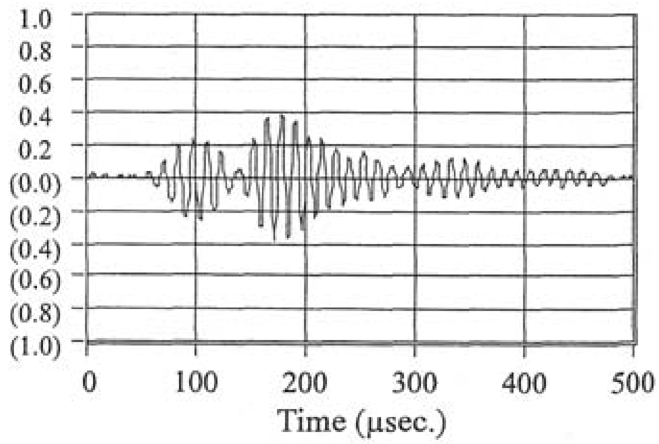

Figure 7.–*Time-waveform signal through honeycombed section of wood.*

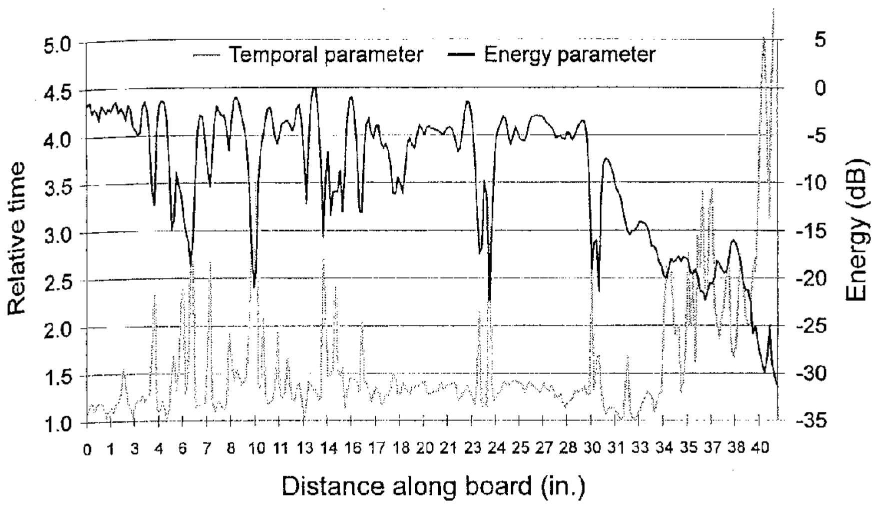

Figure 8.-*Plot oftemporal and energy parameters as a function ofposition on the sample board.*

Conclusions

Commercialization of this technology will have significant impact on the hardwood lumber industry. Specifically, the proposed system has the potential for significant improvements in:

- energy efficiency, by sorting out the wetwood so that the kilns may be run as efficiently as possible;
- material utilization, by allowing the wetwood lumber to be identified, sorted, and dried separately (potentially recovering 10% of current production); and
- production efficiency, by identifying defective dried lumber before it undergoes value-added processing (planing, milling, etc) (1,4, 6,14,16).

The testbed system described here is the first step in the overall commercialization process, providing a flexible tool for evaluating design and analysis parameters. The system is being used to examine a large number of boards of different condition, species, etc., both at the Forest Products Laboratory and on a mobile basis at a number of mills. The operational experience using the testbed will form the basis of the eventual commercial product.

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