Using Ultrasound to Detect Defects in Trees: Current Knowledge and Future Needs

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Abstract— Ultrasonic decay detectors (UDDs) have been available commercially for several years and can be used successfully to detect decay in live hardwood and conifer trees. Recently, a UDD has shown promise in detecting bacterial wetwood in red oaks in the southern United States and in a Chilean hardwood species. Two improvements to the UDD tested would make it more useful to the broader forestry community. Current UDDs only measure ultrasound signal time of flight (i.e., velocity) from the transmitter to the receiver across the diameter of a tree. This measurement is insufficient to distinguish wood decay from a void, or either of those from the cell wall degradation caused by bacterial wetwood. Further, in order to position ultrasonic transducers in contact with the wood of a live tree for good signal propagation, a "wad" punch is used to create 5-cm diameter holes in the bark. This process takes time and causes wounds that serve as entry points for pathogens and insects. An overview is presented of the current effort to develop a UDD that records time-domain and frequency-domain waveforms that can be positively linked to individual types of defects, and that uses smaller, pointed transducers to minimize tree wounds. Preliminary results support current knowledge regarding ultrasound interactions with sound and unsound wood, and suggests that further experimentation can lead to a new generation of UDDs.

INTRODUCTION

Foresters need to identify and assess the extent of damage from wood decay fungi and bacteria in the wood of living trees because damage by these organisms affects subsequent processing for wood products. From a wood utilization perspective, it is also important to distinguish between pathogen-caused wood degradation and macroscopic flaws (e.g., splits). A forester who is aware of the types and extent of pathogen-caused damage in a forest stand is better equipped to prescribe silvicultural and other management practices. Similarly, arborists faced with deciding whether or not to remove a landscape tree would benefit from knowing the severity of heart decay or other types of lower stem damage. The challenge to researchers and developers is to provide foresters, arborists, and other forest health practitioners with an easy-to-use, field portable instrument that will aid them in detecting different types of internal damage in trees, while minimizing the need to wound or damage subject trees in the process. An effort is underway to develop and field test a prototypical instrument that uses ultrasound to detect abnormalities in wood structure. Preliminary research findings are presented along with plans for future research and development.

DISEASES AFFECTING HEARTWOOD

Significance of the problem

It is estimated that for every 100 million board feet of timber harvested every year in the United States, heart decay fungi destroy about 30 million board feet of timber volume. Heart decay is thought to cause more than twice as much timber volume loss as all other hardwood and conifer diseases combined (Tainter and Baker 1996). Boyce (1961) in his book on forest pathology stated that there are so many decays caused by such a large number of wood-destroying fungi that he could only briefly discuss the most important ones. The greatest number of these fungi can decay dead wood while a smaller number of fungi can extensively decay heartwood in living trees.

Practically all hardwoods and some conifers are susceptible to bacterial wetwood infections (Tainter and Baker 1996). Bacterial wetwood has a large economic affect on the hardwood lumber and veneer industry causing problems with color, drying, and machining and reducing overall quality and value (Ward 1982). In 1990, the value of hardwood lumber at point of production in the eastern United States was more than $3.5 billion (Murdoch 1997). Nearly 25% of hardwood sawtimber in eastern forests is in the red oak species group. It has been estimated that bacterial wetwood causes annual losses due to drying defects in oak lumber of about 500 million board feet (Ross et al. 1995). Clearly, with this much economic value at stake, the development of an instrument that can detect wood decay and bacterial wetwood would greatly benefit forest managers of private and public lands. Governmental and private timber sales nationwide would benefit from more accurate volume estimates taking into account volume lost to diseases. It would also be difficult to estimate the importance of this kind of instrument to the arboriculture industry in terms of economic value and job performance.

Heart Decay vs. Bacterial Wetwood

Wood decay fungi cause heart rots in conifers and hardwoods by secreting extracellular enzymes, which break down the structure of host cell walls. When decay is advanced, the breakdown in cell structure usually causes wood tissue to be discolored, soft, and crumbly. In the most severe cases, decayed wood may have the consistency of pudding. In terms of ultrasound wave conduction, the effect of wood in this condition is similar to that of a void through which little energy is transmitted.

Bacteria can cause a disease condition in both conifers and hardwoods known as wetwood, or bacterial wetwood. Unlike the total, or near total, destruction of cell wall integrity that occurs in the decay process, the cells in wetwood-affected heartwood remain intact structurally but may be separated from neighboring cells. This situation occurs because wetwood bacteria secrete extracellular enzymes that degrade the middle lamellae and pit membranes of cell walls while leaving the majority of the cell wall intact (Tainter and Baker 1996). Wetwood-infected lumber that is dried under a normal kiln-drying schedule typically develops defects in the wood such as 'honeycombing', the radial separation of cells along the rays, and 'shake', due to cell separation tangentially along the rings. The slipping or pulling apart of neighboring cells from each other due to the enzymatic breakdown of cell wall structure causes these conditions.

DETECTING WOOD DECAY IN LIVING TREES

Traditional Methods

In the absence of visible indicators of disease such as: open wounds; swellings; darkened, stained bark; or fruiting bodies, it is not easy to determine the existence or extent of a disease in a tree. Even when visible indicators are present, foresters and arborists must estimate the internal radial and longitudinal extent of an infection within a tree bole. This estimation is often done using knowledge gained as a result of having harvested similarly diseased trees or, alternatively, by striking a tree, with a mallet or the back of a hatchet, along the bole and around its circumference while listening for a change in pitch to indicate the transition from sound wood to decayed wood. This second method, called 'sounding', tends to underestimate the extent of decay because it is not refined enough to distinguish between sound wood and incipient decay, and because the average person can 'sound' a tree only to a height of about eight feet above the ground. Using an ultrasound decay detector in a fire-damaged stand of bottomland hardwoods in the Delta National Forest near Rolling Fork, MS, Leininger (unpublished data) verified the presence of heartwood decay at least three feet higher on the bole of a mature green ash *(Fraxinus pennsylvanica* Marsh.) than was evident using the sounding technique. The extent of the rot column was verified by felling the tree.

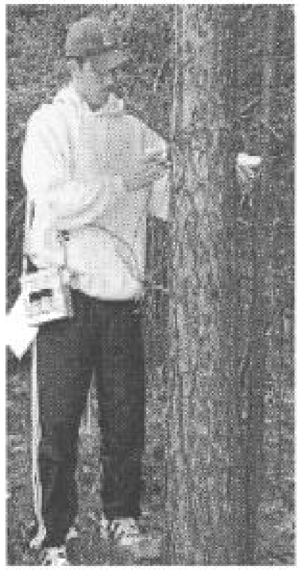
Examination Tools

A number of other methods that employ various instruments have been used to detect wood decay in the absence of visible indicators; Dolwin et al. (1999) provided a review of these. Portable hand or electric drills or steel rods can be used to probe the extent of superficial decays and, to some extent, the severity of decay based on resistance of the wood to penetration by the probe, and on the color and consistency of wood shavings. An increment borer can be used to extract a core of wood extending from the bark into the pith; the core can be examined for signs of decayed, discolored, water-soaked, and malodorous tissue, all of which are indicative of disease. Micro-drills, resistographs, fractometers, and compression meters have been used with varying degrees of success to detect wood quality in live trees and all have the same common drawback; they require use of a either a drill or an increment borer, both of which leave wounds that can be invaded by pathogens and insects (Dolwin et al. 1999). Filer (1970) experimented with the transmission of gamma radiation through stems of standing trees to detect decay; Miller (1988) built a portable x-ray tomography device for utility pole inspection. Shigo and Shigo (1974) pioneered the use of differences in electrical resistance between decayed and sound wood as a means of detecting decay. Gamma radiation equipment proved to be too bulky for field use, and electrical resistance in trees is too variable to provide a reliable measure of wood structural integrity and requires wounding the tree by drilling holes for the electrical resistance probes.

Sonic Devices

McCracken and Vann (1983) were among the first to present data showing that signal attenuation of sound waves (100 Hz and 1 kHz) fromvibrations pulsed through tree stems was different for stems with heart rot than for those without. Using a commercial ultrasound instrument (James V-meter), those investigators also found a direct relationship between the diameters of healthy trees and the time of flight (TOF) of ultrasound waves at 54 kHz and 150 kHz. Transit times were unaffected by variations in moisture content or specific gravity for eastern cottonwood *(Populus deltoides* Bartr.), green ash, and willow oak *(Quercus phellos* L.). However, wood decay increased apparent ultrasound TOF in all three species, a finding that is the basis for ultrasound detection of decay in trees. McCracken and Vann also observed that good contact between the tree and the signal transducers was very important. They reported that reducing the bark to a thin layer greatly reduced TOF variability and signal attenuation, but it also caused damaging wounds to trees. These two issues; the need to reduce signal attenuation across bark and wood in various states of health or decay, and the related issue of needing to minimize or eliminate tree wounds during measurements, are two important challenges to successfully using this technology.

Figure 1. The Arborsonic Decay Detector can be readily transported throughout the forest as its portability permits quick and simple tree inspection.



Since the early 1990s, ultrasound decay detectors (UDDs) have been available to the arboriculture community. The Arborsonic Decay Detector (ADD, Fujikura Europe Limited, Wiltshire, England) is one implementation of this type of device, which is compact and portable (Figure 1). The ADD produces an ultrasound signal of 77 kHz, which according to the manufacturer's operational guide traverses a tree of any species at a relatively constant speed of 2000 ms^{-1}, up to a maximum diameter of 1.4 meters (Anon. 1995). Dolwin et al. (1999) reported variation in the actual signal velocity from about 1600 to 2000 ms^{-1}, and that signal attenuation occurs in trees greater than 1 m diameter. The ADD was designed specifically to detect heart decay in trees.

Because sound is an elastic wave, any disruption of the wood structure (e.g., decay, bacterial infection, or other flaw) that is different from sound wood will affect ultrasonic signal propagation. This phenomenon can be seen by comparing the signal strength of a waveform received for wood containing a defect to the greater signal strength of the waveform for sound wood (Figure 2). While most types of wood defects affect ultrasonic signal strength (Kabir et al. 2000), the current ADD only measures signal time of flight. The ADD developers reasoned that any decay present in the signal path would either cause the signal to take a longer path to the receiver using good wood for propagation (greater time of flight), or cause the signal to weaken to the point that it could not be detected above a preset threshold (a "timed-out" condition). The problem with this approach is that there is no way to determine if a "time-out" condition was caused by disease, a void, or if there was bad transducer-to-wood contact. Recognizing this problem, Beall and others used ultrasound time and frequency domain parameters to detect decay and other defects in softwood utility poles and round wood sections of softwood (Beall 1996; Beall et al. 1994; Tiitta et al. 1999), but they did not demonstrate the ability of these parameters to detect bacterial wetwood and other defects in living trees, especially bardwoods.

Using the ADD, heart decay is defined by a propagation time (in µsec) that is three-fourths or more of the tree diameter in millimeters. Sound wood is defined by a propagation time that is one-half or less the tree diameter in millimeters. Based on this relation&p, a propagation time of 400 µsec, or less, for an 800 mm diameter tree indicates sound wood. Whereas a propagation time of 600 µsec, or more, indicates heart rot. A wave propagation time within the 700 µsec range between the 400- and 600-µsec thresholds could indicate incipient decay according to the manufacturer of the ADD, and thus warrants further examination. Xu et al. (2000) found that wave propagation times falling between those two thresholds in red oaks in Mississippi and South Carolina were indicative of bacterial wetwood infections. In the following section, we review past approaches to identifying wetwood using both chemical/water relations and ultrasonic measurements.

DETECTING WETWOOD IN LIVING TREES

Chemical Methods

Wetwood bacteria produce acetic acid and other fatty acids that have a distinct rancid, vinegar-like odor (Schink and Ward 1984). The easiest and most reliable way to discern bacterial wetwood outside the laboratory is by sniffing to detect these odors at their source; for example, increment cores, log ends, or milled lumber from freshly cut trees. This is problematic, however, as different individuals vary in their ability to detect odors.

Increment coring, which is inconvenient and damages the tree, is the only way to detect bacterial wetwood in standing trees while in the field. An effort was made to develop an enzyme-linked immunoassay to detect wetwood bacteria, but a working system is still years away (McElreath et al. 1995, 1997a and b, 1998). Field and laboratory studies have revealed certain characteristics about the chemical, physical, mechanical, and drying properties of bacterial wetwood in red oaks. Methane concentration was the best indicator of wetwood in living red oak trees sampled in Mississippi, South Carolina, and Florida, whereas other associations with wetwood—greater concentrations of acetic acid, and total K^+, and lesser concentrations of nonstructural carbohydrates—depended on the severity of wetwood rather than occurrence alone (Xu et al. 2001a). In a related study, Xu et al. (2001b) found that wetwood-affected red oaks in Mississippi and South Carolina were characterized by greater moisture content, abnormally high radial and tangential shrinkage, and lower tension strength perpendicular to the grain compared to wood from healthy red oaks. In addition, moisture content of increment cores was a good indicator of wetwood in the heartwood of sampled red oaks.

Figure 2. Normalized signal strength (volts) is plotted against time (µsec) for an ultrasonic signal propagating through wood with or without a defect. The time of flight is relatively unaffected by the defect, but there is substantial energy loss.

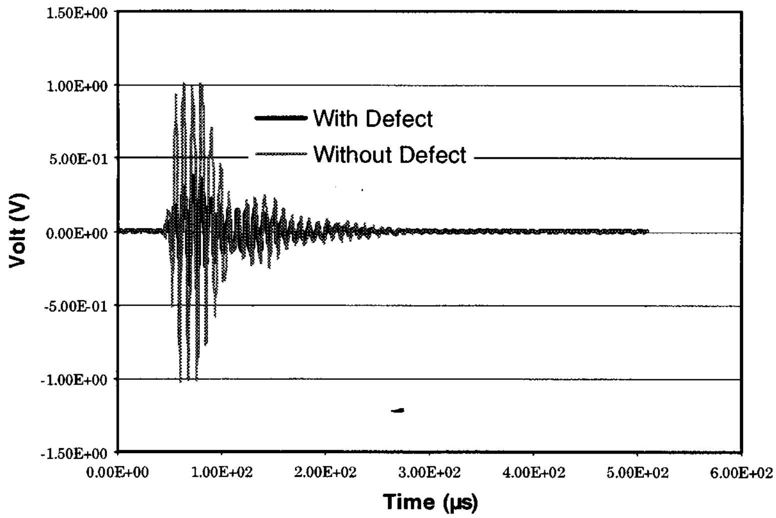


Figure 3. Graph of linear regression lines of ADD readings for trees in Mississippi that were healthy (#), had bacterial wetwood (+), or had decayed heartwood (•).

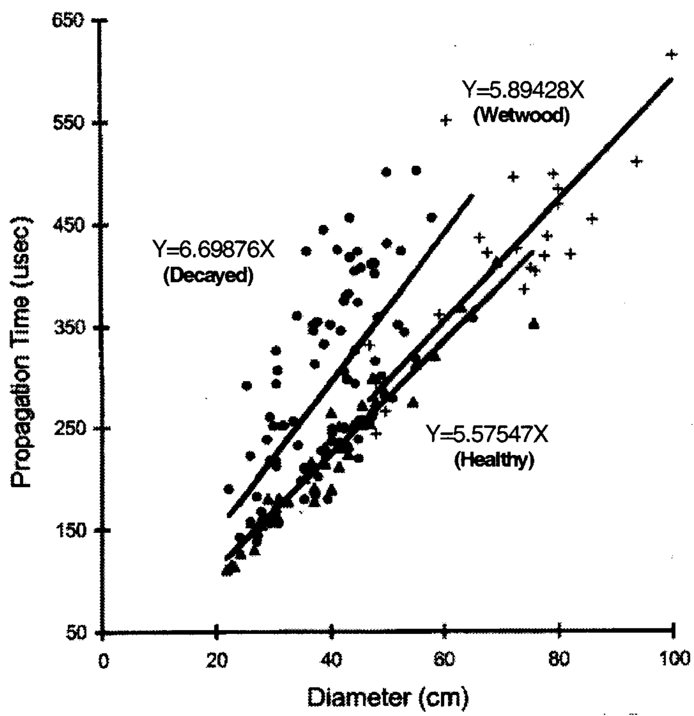
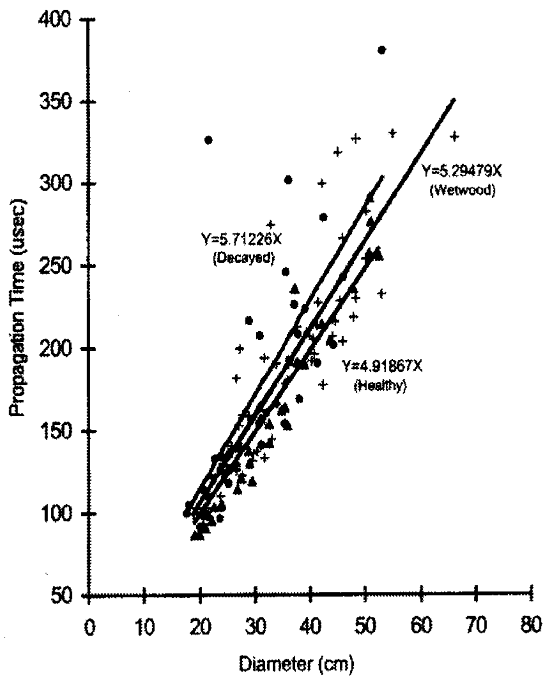


Figure 4. Graph of linear regression lines of ADD readings for trees in South Carolina that were healthy (#), had bacterial wetwood (+), or had decayed heartwood (•).



However, the potential of these variables to be wetwood indicators depends on the severity of the wetwood infection and involves destructive sampling. Increment cores to the heartwood might have to be removed from several places on the butt log of a large oak to adequately sample for wetwood. This procedure is time consuming, injures the tree, produces entry points for other pathogens, and reduces the dollar value of the log once it is harvested.

ADD Inspection

Xu et al. (2,000) and Tainter et al. (1999) used the ADD to detect bacterial wetwood infections in red oaks *(Quercus* spp.) and the Chilean hardwood tepa *(Laureliopsis philippiana* [Looser] Schodde), respectively. In the red oak study, ultrasound detection of wetwood and heart decay was compared. Healthy, heart-decayed, and wetwood-infected willow and nuttall *(Quercus nuttallii* E.J. Palmer) oaks were examined in Mississippi, while in South Carolina, northern red oaks *(Q. rubra* L.), southern red oaks *(Q. falcata* Michx.), black oaks *(Q. velutina* Lam.), and scarlet oaks *(Q. coccinea* Munchh.) were tested. A complete description of the experimental approach and methods is given in the original report (Xu et al. 2000).

Regression lines relating ultrasound propagation times to bole diameters for healthy, wetwood-infected, and heartwood-decayed sample trees in Mississippi are graphed in Figure 3. The slopes of the lines of heartwood-decayed trees differ from those for wetwood trees (P=0.0001) and healthy trees (P=0.0001). There is no difference between the slopes of lines for wetwood-infected and healthy trees (P=0.0607), although the regression lines are close to being significantly different. When heartwood-decayed trees are included with wetwood trees, there is a significant (P=0.0001) difference between slopes of regression lines of this combined group and healthy trees.

There is no significant difference between any of the regression lines relating ultrasound propagation times to bole diameters for healthy, wetwood-infected, and heartwood-decayed trees in South Carolina (Figure 4). However, when heartwood-decayed trees are combined with wetwood trees, there is a significant difference (P=0.0241) between that combined group and the healthy trees.

For the ADD readings of Chilean tepa logs, there was a significant difference between the slopes of the two regression lines (P=0.0022), one representing unstained logs, the other representing logs with butterfly stain (Figure 5). Significance between the slope coefficients of the two lines was tested using the dummy variable approach presented by Gujarati (1995). The relationship between propagation time readings and log diameter was very strong for unstained logs (R^2=0.97) and for logs with stain (R^2=0.97). Because both lines were forced through the origin (0,0), the lines are close together for small diameters and diverge as log diameters increase. The significant difference between the slopes of these two lines indicates that the ADD shows promise for detecting butterfly stain in tepa logs (or trees), especially for larger diameters.

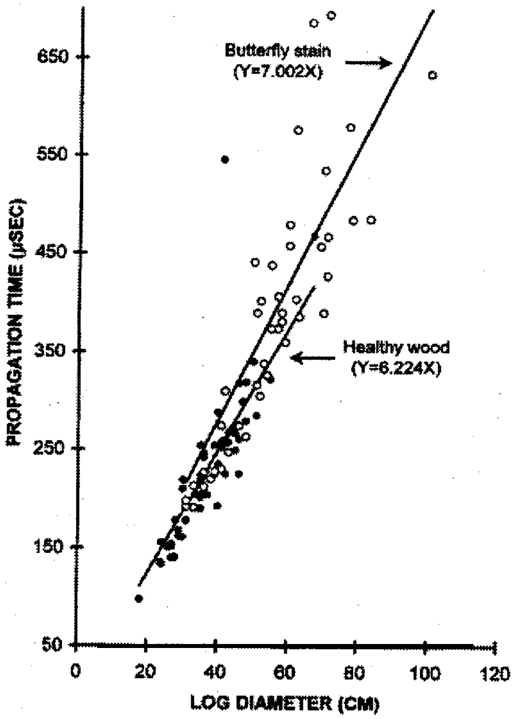
Development of an ultrasonic decay detector that can distinguish between incipient decay, voids, and bacterial wetwood, in addition to detecting advanced decay, would be a big improvement over existing devices. Two other major drawbacks of the ADD are, first, that two, 5-cm diameter wounds to the xylem are required for each ultrasound reading; and, secondly the ADD is engineered to detect a signal with a threshold amplitude, thus providing limited electronic information even though more signal information may be available.

IMPROVING ULTRASOUND DETECTION OF INTERNAL DAMAGE

Results to date with the ADD are encouraging. However, the use of TOF-diameter relationships (effectively velocity) lacks discriminating ability (substantial overlap exists in the data points) and seems to be somewhat species dependent, as is evident when multiple species are included in the analyses. With the current stage of ADD technology, a particular TOF value for a tree with a particular diameter cannot reliably predict which of several internal defects are present. We have concluded that ultrasound velocity measurements alone are unlikely to provide sufficient information to overcome these problems.

Related work on inspection of pallet parts suggests that we should be able to distinguish different types of internal tree damage using ultrasonic measurements. Using fresh-cut (green) pallet deckboards of northern red oak and yel-

Figure 5. Graph showing the relationship between regression lines of healthy (o) and butterfly-stained (•) tepa logs



low-poplar *(Liriodendron tulipifera,* L.), Kabir et al. (7,001) characterized a variety of defect types with ultrasound, including decay and voids. Several TOF, energy, and pulse length variables were measured. While no single ultrasound variable appears able to discriminate between all defect types, some subset of those variables taken together should be able to classify different defect types. Measurements in those experiments, however, were taken directly on, or adjacent to, particular defect types. This situation differs from heartwood defects in standing trees where internal degradation is surrounded by clear wood regions in most cases. Furthermore, those pallet part experiments did not include wetwood as a defect type. Consequently, a preliminary set of tests (using larger pallet parts) was performed to illustrate how ultrasonics might be used to distinguish between sound wood, decay, wetwood, and voids in standing trees.

Pallet Stringer Tests

Three red oak pallet stringers and one red oak pallet deckboard that included sound wood, advanced decay, a void, or wetwood were collected from a local pallet manufacturer. For the wetwood sample, a stringer was not available, so a deckboard part was used. Based on the intensity of odor, this wetwood sample was classified as moderate infection. Pallet stringers tested were approximately 3.8 cm (1.5 inches) thick; the deckboard was 1.6 cm (0.625 inch) thick. Drilling a 1.25 cm bole (0.5 inch) longitudinally into the center of the specimen simulated the void sample. Because pallet parts are cut from green cants, the moisture content is similar to that for live trees. Ultrasonic measurements were made in a pitch-catch arrangement from face to face, primarily a radial direction–similar to diameter measurements on standing trees. Measurement regions of the stringers were selected such that ultrasound transmissions traversed both sound and unsound wood, similar to transmission through good sapwood and defected heartwood in a standing tree. Aside from destructively sampling trees for defects of interest and conducting ultrasonic tests on those specimens, these "simulated tree" tests closely approximate the essential characteristics of actual measurements on standing trees without any bark-related attenuation problems.

An industrial prototype ultrasonic scanning system (Kabir et al. 2001) was used to take measurements on the samples. All measurements were carried out at 120 kHz transmitting frequency and received signals were sampled at 500 kHz. The transmit voltage and receiver gain were 130 V and -4 to -1 dB respectively. Several measurements were taken to ensure that the captured signals were representative of the internal condition being sampled.

Utrasonic time-domain waveforms appear in Figure 6 for the four samples tested. Compared to sound wood, the loss of internal wood integrity for decay, wetwood, and void samples is evident in their greatly reduced signal strength. Because signal strength as a function of time aggregates the contributions from all frequencies, it provides limited information. By applying a Fourier transformation (FFT) from the time domain into the frequency domain, we can obtain a more detailed picture of bow wood characteristics influence ultrasound propagation. Figure 7 displays the FFT magnitude graphs for our samples. For each spectra, energy values peak at the transmit frequency of 120 kHz. Again, as in the time-domain graphs, the sound wood sample has the highest peak energy. The wetwood sample has an intermediate peak energy value, which distinguishes it from decay and void. The decay spectrum depicts greater signal attenuation than the bole spectrum in frequencies above the peak frequency; this is consistent with results on decayed wood by other researchers (e.g., Halabe et al. 1995). There are a variety of ultrasonic parameters that can be calculated to quantitatively capture what we see in these graphs, and that can then be used to distinguish one wood type from another.

These tests are very preliminary and only make use of a single test specimen in each case. Nevertheless, the results are consistent with our knowledge of wood structure and ultrasonic propagation in that medium and with prior wood scanning results. If these ultrasound signatures can be reproduced consistently in other samples and other species, they can form the basis for a new generation of UDD.

Nondestructive Transducer Contact

Because tree bark provides a sound propagation interface (reflecting substantial energy) and uneven contact

Figure 6. Time-domain waveforms plot energy (volts) versus time (µsec) for (a) sound wood, (b) advanced decay, (c) a hole, and (d) wetwood. After reaching peak energy, signal strength gradually decreases until the sampling window of 256 µsec is exceeded.

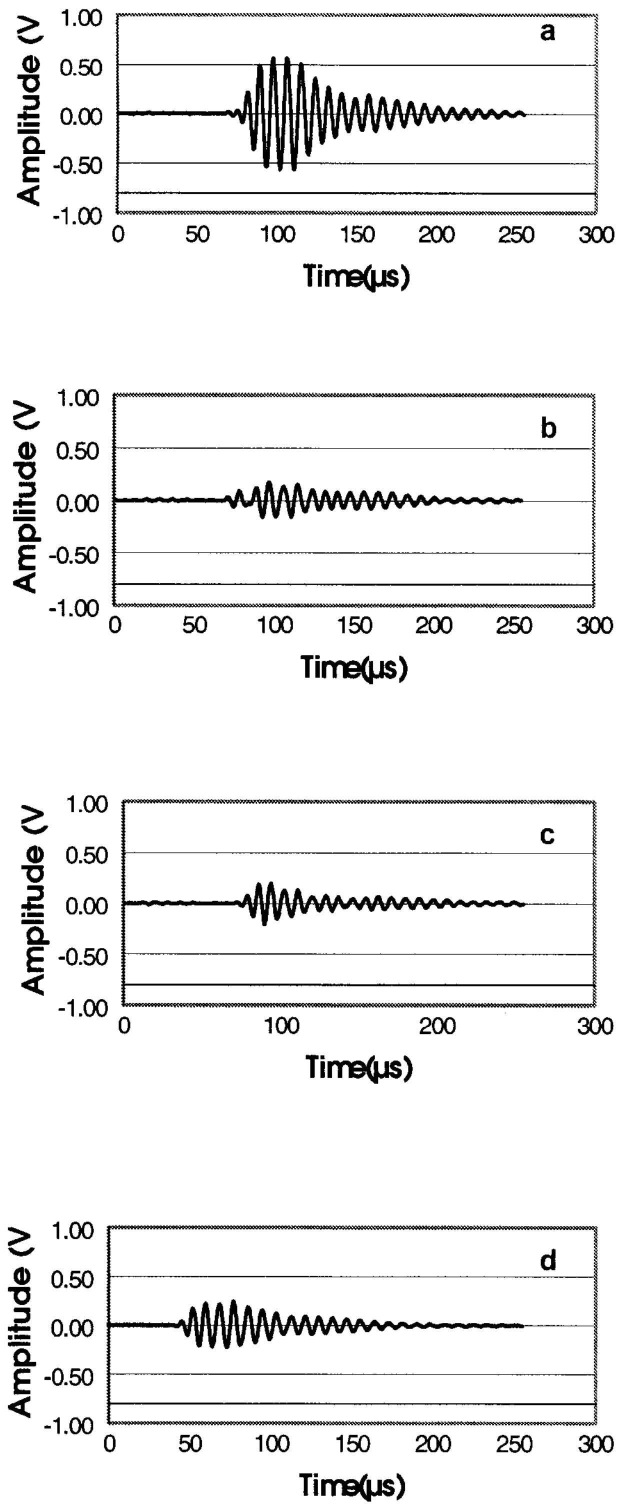
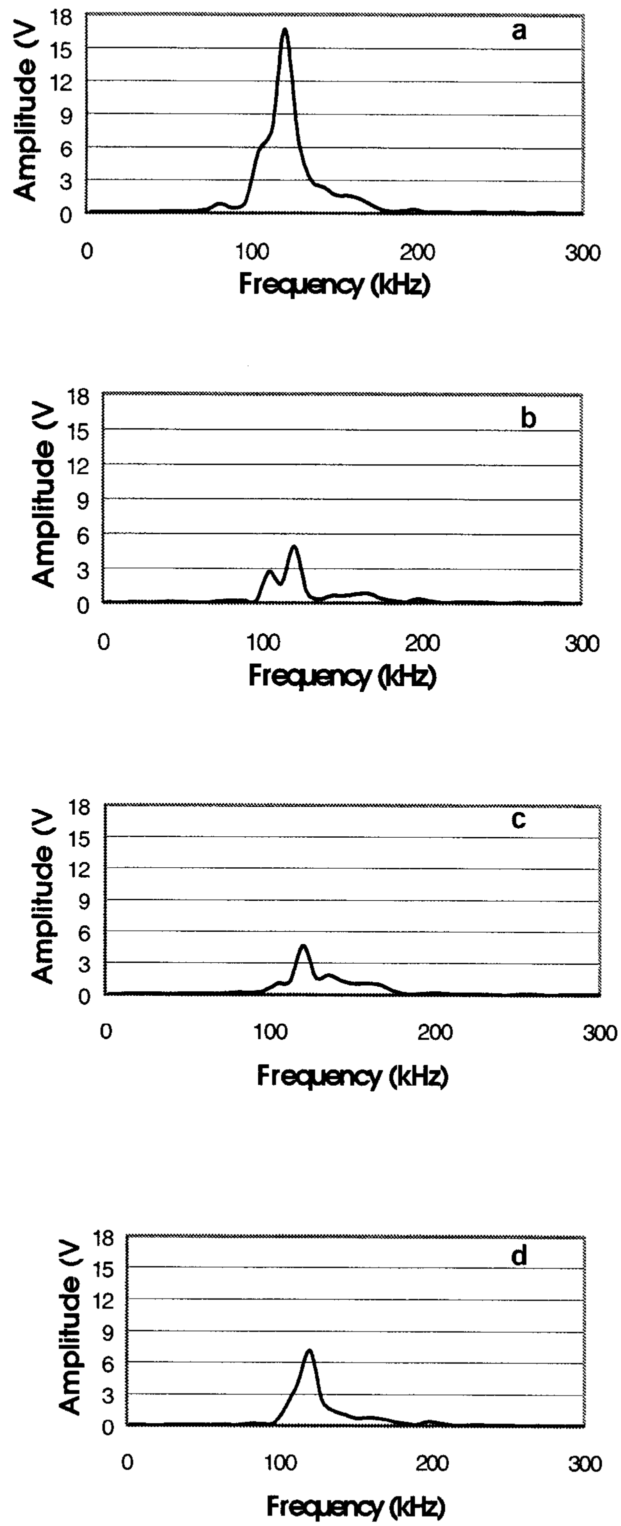


Figure 7. Fourier transformation (FFT) graphs for the four samples plot signal amplitude (magnitude of the FFT) versus frequency (kHz): (a) sound wood, (b) advanced decay, (c) a hole, and (d) wetwood. Energy is at a maximum near the transmitted frequency of 120 kHz.



with transducers, there is often great signal attenuation. But removal of bark and xylem is highly undesirable, as noted above. Therefore, bark must be penetrated in some way to achieve good signal transmission. For the ultrasound frequencies that we are interested in transmitting, relatively large (2.5-4 cm diameter) cylindrical transducers are most efficient. However, market needs have not driven any search for alternative transducer designs. Recently, though, wood scanning efforts by Perceptron, Inc. (Ultrasound Technology Group) have led to the development of a more conical transducer with some bark penetration capability. These transducers have a contacting face of about 1 cm in diameter, yet they operate in the desirable frequency range for wood inspection. It is possible that these transducers could be held in place by hand–or mounted on some sort of hand-held device (perhaps using a scissoring caliper action)–that would supply sufficient pressure for bark penetration with negligible bark and xylem damage. Most thick-barked trees have deep fissures in their bark that could provide adequately wide access points for such transducers. In addition to tests that determine ultrasound relationships for internal tree damage, we would need to verify the reliability of this transducer-wood contacting mechanism across of variety of species and bark characteristics.

CONCLUSIONS

The operating principles inherent in the current generation of UDDs can only be marginally effective. While TOF measurements are useful for interrogating standing tree quality, they are conceptually flawed and provide only ambiguous readings. When no signal is received across the stem, it is impossible to distinguish between bad transducer contact with a tree and internal damage. Furthermore, different types of internal damage cannot be readily discriminated. Foresters and arborists need more diagnostic equipment to perform their jobs effectively.

Both past ultrasonic experiments on wood and preliminary tests reported here suggest that a more sophisticated and robust device can be built. Furthermore, our preliminary tests suggest that it might be experimentally expedient and advantageous to conduct additional laboratory tests using small samples as we have done here. After the ultrasonic relationships are better understood using laboratory experiments, then more elaborate, destructive field tests could be conducted on standing and felled trees. These full-scale tests would help fine tune the relationships identified in the laboratory and would also address less idealized conditions, e.g., simultaneous occurrence of several types of internal damage, transducer-to-wood contact and bark penetration.

Further research and development goals to improve upon existing UDD technology should include designing the electronics to analyze important waveform patterns indicative of advanced decay, incipient decay, bacterial wetwood, and voids. Ultrasound signal transmission and reception should occur through transducers that are the most "tree friendly" method available. Once a working prototype is developed, meaningful statistics relating sample trees to the larger forest resource should be developed to provide the broadest use for the new device. The final goal is to bring this improved technology into the marketplace as a field-portable, affordable unit.

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