# Evaluation of Acoustic Tomography for Tree Decay Detection

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## Abstract

In this study, the acoustic tomography technique was used to detect internal decay in high value black cherry (*Prunus serotina*) trees. Two-dimensional images of the cross sections of the tree samples were constructed using PiCUS Q70 software. The trees were felled following the field test, and a disc from each testing elevation was subsequently cut and evaluated in the laboratory. It was found that acoustic tomography is capable of detecting internal heartwood decay in black cherry trees. Comparison of the acoustic tomograms with photographic images and hardness mappings of the discs revealed that the prediction of decay areas by acoustic tomography is rather conservative when heartwood decay is the major structural defect in trees. When an internal crack is present in the tree trunk, acoustic tomography tends to overestimate the size of defect. This highlights the importance of determining the nature of structural defects when assessing hardwood trees using the acoustic tomography technique.

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## Introduction

A large percentage of the living trees in the forest contains internal decay that significantly reduces their economic value. It is estimated that for every 100 million board feet of timber harvested in the United States annually, 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). Early detection of internal decay in living trees, particularly in hardwood trees, could provide a significant benefit to the forest industry in terms of making accurate quality assessments and volume estimates and best utilizing the resources.

Acoustic tomography is a technique that has been explored by many researchers in the area of urban tree decay detection (Divos and Szalai 2002, Nicolotti et al. 2003, Socco et al. 2004, Wang et al. 2005, Wang et al. 2007). It has proved to be successful in detecting internal structural defects and helping to determine the stability of large trees in parks. This nondestructive imaging technique is based on simultaneous measurements of the time of transmission of acoustic waves by multiple sensors arranged around the trunk. It provides a two-dimensional image of the cross section that illustrates the physical conditions of the trunk (Bucur 2003, Wang et al. 2004). Because of its significantly low cost compared to X-ray computed tomography in medical applications, this technique has attracted attention in wood and urban forest communities. The application of acoustic tomography in urban tree inspection is increasing.

Gilbert and Smiley (2004) evaluated an acoustic tomography tool for its ability to quantify decay in white oak (*Quercus alba*) and hickory (*Carya* spp.). They reported a high correlation between the amount of decay detected by the tool and the amount actually present in the cross section. The average percentage accuracy for samples in which decay was present was 89 percent. Rioux (2004) tested 10 white oak and three hickory trees with sonic tomography. He found that when decay was present, differences between data obtained by the apparatus and actual values were on the average of 5 percent. The investigation on century-old red oak trees by Wang and Allison (2008) also showed great success in utilizing the acoustic tomography technique to detect internal structural defects and identify the general location and approximate magnitude of the defects.

The objective of this study is to take the acoustic tomography technique one step further – into the forest to determine the feasibility of using this novel technique for detecting internal decay in high-value hardwood trees standing in the forest.

## Materials and Methods

### Tree Sample Selection

Twelve black cherry (*Prunus serotina*) trees were selected from a stand of second-growth Allegheny hardwoods in Kane, Pennsylvania. The forests of the Allegheny Plateau are widely recognized for the quality of the black cherry timber that grows there. More than one-third of the cherry veneer logs sold in world markets originate from these forests. The tree selection procedure employed involved two steps: initial screening and final sample tree selection. The goal of our tree section procedure was to obtain trees with different levels of internal decay. For comparison purposes, healthy trees were also included in the experimental plan.

During initial screening, 20 black cherry trees were pre-selected through visual examination and a single-path stress wave test. These pre-selected trees had a wide range of physical conditions in terms of physiological characters and stress wave transmission times. From these 20 trees, we then selected 12 sample trees for the main purpose of this study.

### Field Acoustic Tomography Test

Twelve sample trees were nondestructively tested in the forest using a multi-channel acoustic measurement system – PiCUS Sonic Tomograph (Argus Electronic Gmbh, Rostock, Germany).

The sample trees were first tested at about 50 cm above the ground. When potential internal decay or defects were identified in the acoustic tomogram obtained at this elevation, two more tests were then conducted at higher elevations of the trunk, one at 100-cm level and one at 150-cm level. Upon completion of acoustic measurement at each level, a tomogram was constructed for the cross section using the PiCUS Q70 software (Argus Electronic Gmbh 2006).

### Visual Assessment and Hardness Mapping

After acoustic tomography tests were completed, all of the sample trees were felled and a 5.1-cm- (2-in.-) thick disc was cut from each test location. The sample disc was subsequently labeled with tree number and elevation (e.g., no. 1-50). A digital picture of the cross section was taken of all of the freshly cut sample discs. After the discs were shipped to the laboratory, they were visually examined for internal condition in terms of discoloration and severity of location of decay.

To quantitatively assess the tomograms of the trees, seven discs were selected to develop hardness maps of the cross sections through laboratory hardness testing. **Figure 1** shows the 2.54 by 2.5 cm (1 in. by 1 in.) grids that guided the hardness testing on the top surfaces. Disc samples were conditioned to 12 percent equilibrium moisture content (EMC) in an environmental chamber before hardness testing.

The hardness of the disc samples was obtained using the Janka ball hardness test procedure given in ASTM D 143 (ASTM 2005). The hardness test was conducted on each cell using indentation on the cross-section face. The test set-up (Instron testing machine with a standard 0.444-in.-diameter steel ball mounted on the crosshead) allowed continuous recording of load as a function of penetration depth of the steel ball into the wood. A threshold was set to automatically record the "maximum load" at an indentation of 5.64 mm (0.222 in.) as specified in ASTM D143. The hardness values obtained from each disc were used to determine the distribution of hardness in the cross sections. A three-dimensional mapping of hardness was generated for each tested disc using the Matlab software.

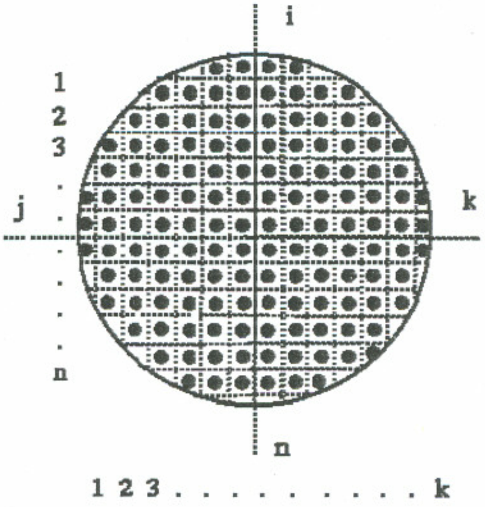


**Figure 1.**—*Schematic of hardness mapping grids.*

## Results and Discussion

**Table 1** shows the results of single-path stress wave tests and visual assessment of the black cherry trees. The radial stress wave velocity of the trees provided guidance for selecting tree samples that more likely have a range of physical conditions. Visual grades of the trees were determined based on observations of visual characteristics following the visual grading rules for logs. Of the tree samples finally selected, four trees were visually determined as grade 1, three trees determined as grade 2, four trees determined as grade 3, and one tree was determined as below grade. The diameter at breast height (DBH) of the sample trees ranged from 33.8 to 61.0 cm (**Table 1**).

Visual examination of the discs indicated that black cherry trees diagnosed as defect positive had several different types of structural defects, including heartwood decay, sapwood decay, internal crack, ring shake, and small insect holes. Among them, heartwood decay and internal crack are the most common major defects.

**Table 1**.—*The results of visual assessment and single-path stress wave test.*

| Tree sample no. | DBH (cm) | Acoustic transmission time (μs/m) | | | Visual grade level |
|---|---|---|---|---|---|
| | | A-A′ | B-B′ | Avg. | |
| 1 | 49.5 | 1127 | 1126 | 1127 | 1 |
| 2 | 40.1 | 706 | 787 | 747 | 3 |
| 4 | 61.2 | 614 | 503 | 559 | 1-V |
| 7 | 52.6 | 590 | 620 | 605 | 1-V |
| 10 | 52.6 | 723 | 663 | 693 | 3 |
| 11 | 39.1 | 519 | 604 | 598 | 1 |
| 12 | 33.8 | 579 | 592 | 586 | 2 |
| 15 | 45.7 | 621 | 611 | 616 | 2 |
| 16 | 61.0 | 594 | 700 | 632 | 3 |
| 17 | 40.9 | 586 | 644 | 615 | 2 |
| 18 | 50.8 | 953 | 911 | 932 | Below grade |
| 19 | 58.2 | 1235 | 1192 | 1214 | 3 |

**Figure 2** shows the tomogram and photographic image of a sound tree cross section (tree no. 12 at 50-cm elevation). The acoustic velocity in the cross section was in the range of 1360 to 1484 m/s, with an average velocity of 1404 m/s. The tomogram showed no acoustic shadows (violet, blue, and white areas) in the cross section. Visual examination of the disc revealed that the cross section was mostly clear and sound, which confirmed the acoustic diagnosis. It was noted that a small worm hole (<1% of the cross section) in the disc of tree no. 12 was not detected in the tomogram. This indicated that the resolution of the acoustic tomography is not high enough in detecting such a small defect in trees.

**Figure 3** shows the tomogram and photographic image of a decayed tree cross section (tree no. 1 at 50-cm elevation). The acoustic velocity in the cross section ranged from 574 to 750 m/s, significantly lower that that in a sound tree cross section. The structural defects found in tree no. 1 are the most significant of all of the tested trees

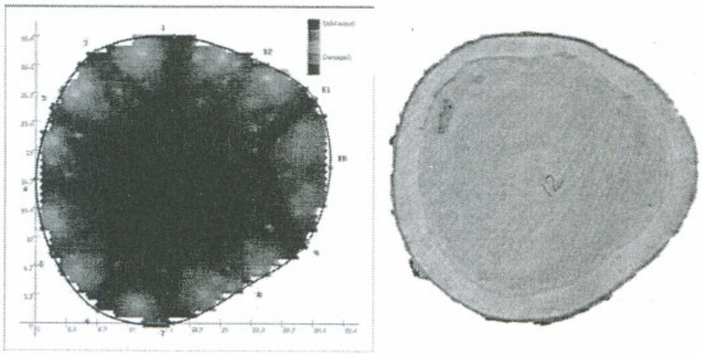


**Figure 2.**—*Comparison of tomogram and disc of tree no. 12.*

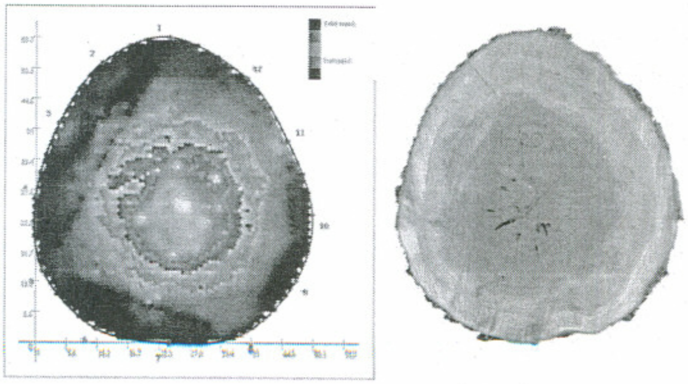


**Figure 3.**—*Comparison of tomogram and disc of tree no. 1.*

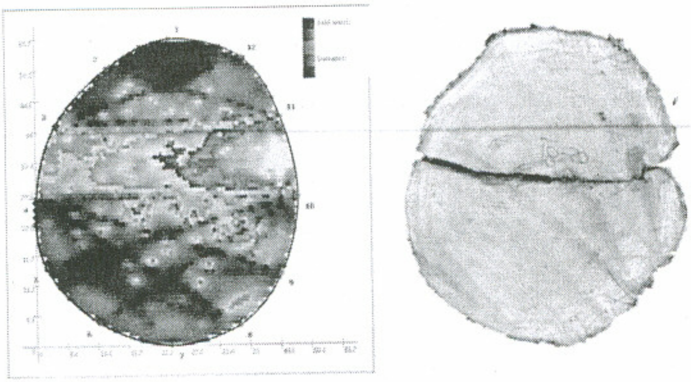


**Figure 4.**—*Comparison of tomogram and disc of tree no. 18.*

with both tomograms and disc images confirming heartwood decay at all three elevations. Laboratory examination confirmed the presence of brown-rot decaying fungus. The tomogram at 50-cm elevation in **Figure 3** showed large acoustic shadows in the central areas of the disc. Visual examination of the disc revealed significant heartwood decay at the same location. Analysis of all of the decayed trees indicated that acoustic shadows in the tomograms were generally in good agreement with the true physical conditions.

**Figure 4** shows the tomogram and photographic image of a tree cross section with a lateral crack (tree no. 18 at 50-cm elevation). In this case, the acoustic velocity ranged from 751 to 1010 m/s in the cross section, which was significantly lower than that of a sound tree, but higher than that of a decayed tree. The tomogram of tree no. 18 contains a big band of acoustic shadow, which expands from one side of the trunk to the other side. Visual examination of the disc revealed a large lateral crack as the dominating structural defect. This crack, laterally crossing the section, extended up and down in vertical planes within the trunk, effectively cut off linear propagation of the acoustic waves diverting them to a much longer travel path. The direct result of this was that, even without significant decay present, the software produced a wide band of acoustic shadow in the tomogram.

To better evaluate the true physical condition and define the boundary of decay in disc samples, we generated two-dimensional hardness distribution figures that show the transition of hardness values in radial direction (from sapwood to heartwood) as well as three-dimensional hardness mappings of the entire cross sections.

**Figures 5 and 6** demonstrates the two-dimensional hardness distributions and the three-dimensional hardness mappings of sound tree cross section (tree no. 12), decayed tree cross section (tree no. 1), and the tree cross section with lateral crack (tree no. 18), respectively. The solid line in **Figure 5** indicates the hardness trend in north–south direction and the dashed line indicates the hardness trend in east–west direction. It was found that hardness of sapwood is significantly lower than that of heartwood in sound tree sections. This implies that when

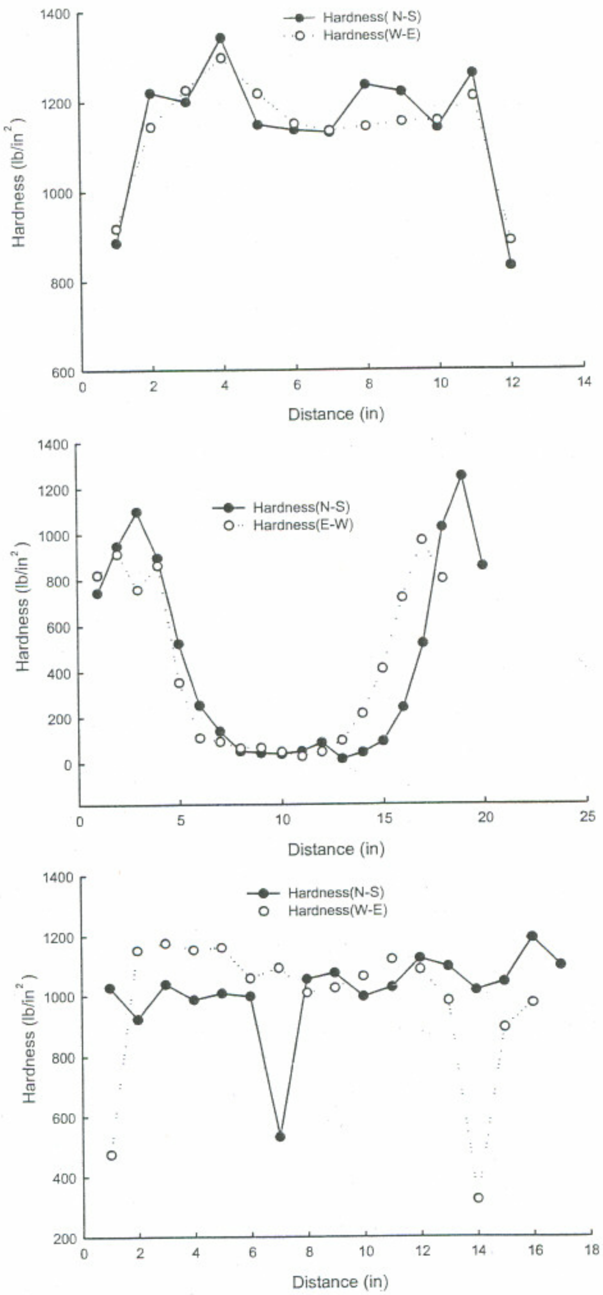
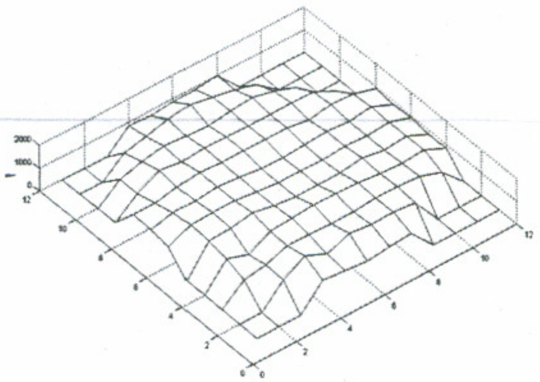
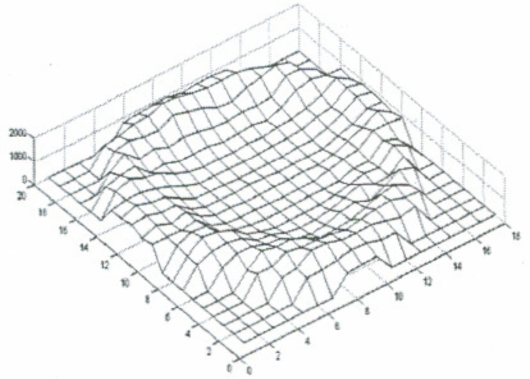


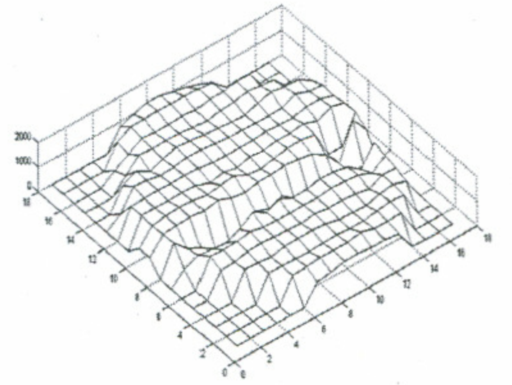
**Figure 5.**—*Distribution of hardness in tree cross sections: sound tree (tree no. 12) (top); decayed tree (tree no. 1) (middle); and tree with internal crack (tree no. 18) (bottom).*



(a) Tree no.12



(b) Tree no.1



(c) Tree no.18

**Figure 6.**—*Hardness mapping of tree cross sections: sound tree (tree no. 12) (top); decayed tree (tree no. 1) (middle); and tree with internal crack (tree no. 18) (bottom).*

assessing the hardness mappings of the cross sections, the hardness values should be interpreted differently in terms of sapwood and heartwood. The distribution of hardness in heartwood area was found relatively flat for sound tree section (e.g., tree no. 12), although certain variations did exist. In decayed tree cross sections (e.g., tree no. 1), however, the hardness values dropped dramatically in central areas, resulting in a large depression zone. This depression zone best defined the size and boundary of the heartwood decay in the cross section. When comparing the two- and three-dimensional hardness figures with the acoustic tomogram, we found that the true decay areas in the cross section apparently exceeded the size of the acoustic shadows in the tomogram, suggesting that decay prediction by acoustic tomography is rather conservative in terms of detecting heartwood decay. In the case of the tree cross section with a lateral crack (e.g., tree no. 18), it was found that the area of acoustic shadows in the tomogram is significantly larger than the defect area mapped by the hardness. This indicated that acoustic tomography tends to overestimate the size of the defect when a crack is present in the cross sections, which is opposite to the phenomena associated with heartwood decay. This highlights the importance of determining the nature of structural defects when assessing standing trees using the acoustic tomography technique.

## Conclusions

The acoustic tomography technique was applied to production forest to evaluate its probability in detecting internal decay in high-value black cherry trees. Based on the preliminary analysis of acoustic tomograms and hardness mapping results, we conclude the following:

- Acoustic tomography proved to be an effective tool for detecting internal decay in black cherry trees. The tomogram can show the location and the relative size and shape of internal decay.
- When heartwood decay is the major structural defect in trees, the prediction of decay areas by acoustic tomography is conservative. The acoustic shadows (violet, blue, and white colors) are significantly smaller than the true decay areas as indicated by hardness mapping.
- When an internal crack is present in the tree trunk, the acoustic tomography tends to overestimate the size of the defect. The acoustic shadows are usually in the form of a wide band and its size is significantly larger than the true defect area.
- The findings of this study highlight the importance of determining the nature of structural defects when assessing trees using the acoustic tomography technique.

## Acknowledgment

This study was funded through a cooperative research agreement between the Natural Resources Research Institute of the University of Minnesota Duluth and the USDA Forest Service Northeastern Research Station. The authors would like to thank the Chinese Academy of Forestry and the USDA Forest Products Laboratory (FPL) for supporting Mr. Shanqing Liang to participate in this study during his 4-month visit at FPL.

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