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Acoustic tomography based on hybrid wave propagation model for tree decay detection

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ABSTRACT

Acoustic wave technologies have been used in wood defect detection for many years. Various tomographic imaging algorithms have been proposed to construct two dimensional acoustic velocity maps that serve as the scientific evidence of tree's internal condition. Many previously proposed algorithms were based on the assumption that acoustic waves propagate along straight rays in the cross sections of trees. To simulate the acoustic wave propagation more realistically, this paper proposed a tomographic imaging method based on a hybrid wave propagation model (HWPM) that includes two velocity inversion phases: straight-ray inversion and curved-ray inversion. The straight-ray inversion was first applied to obtain the preliminary velocity distribution, followed by the curved-ray inversion to refine the velocity distribution. A velocity correction factor was determined for each grid cell following each inversion iteration, and then was used to derive a new velocity value for each corresponding cell. The maximum and minimum velocity constraints were imposed on the newly-computed velocities, and some velocity constraints of grid cells were also imposed to address the nonuniqueness problem commonly existed in velocity inversion and generate a more accurate tomographic image. To evaluate the effectiveness of the hybrid inversion method, we conducted multipath acoustic wave testing on three short log sections (one sound and two with artificial defect) in the laboratory and four live trees in Yangzhou Slender West Lake Park, Jiangsu Province, China. Time-of-flight data was collected by PiCUS Tomograph tool and used to generate tomographic images with both Simultaneous iterative reconstruction technique (SIRT) and the proposed hybrid inversion method to make a comparison. Micro-drilling tests were conducted on the live trees to determine the internal condition and served as the basis for evaluating the tomographic images. Our results indicate that the hybrid wave propagation model is effective in constructing acoustic tomographic images that are reasonably accurate in detecting the internal defects of urban trees.

1. Introduction

Urban trees play a significant role in our daily life and are valuable assets to communities and a healthy environment. Defects, both external and internal, can develop throughout the life cycle of a tree. Detecting the internal structural defects that are hidden from view on tree trunks is a big challenge to arborists and tree managers. Both public safety and urban forest conservation concerns support strong interest in developing and applying more rapid and precise diagnostic tools to detect decay and other types of structural defects in trees (Allison et al., 2006).

Acoustic wave method has proved to be an appropriate technique for assessing internal conditions of wood and locating moderate to severe internal decay in trees (Lin et al., 2013; Gao et al., 2014; Merlo et al., 2014). Comparing to other nondestructive methods such as X-ray, computer tomography (CT), and ground-penetrating radar, acoustic wave techniques are regarded as low-cost, user friendly, and suitable to many field applications (Brancheriau et al., 2012; Wang, 2013). Several commercial acoustic tomography tools (such as ArborSonic 3D Acoustic Tomograph, PiCUS Sonic Tomograph, and ARBOTOM®) have been developed and are currently being used to perform multi-path acoustic measurements on urban trees and obtain two dimensional tomographic images of tree's cross sections. Kana et al. (2015) measured a green disk of Zelkova serrata with different sizes of artificial circular cavities and reconstructed contour map by acoustic tomography. Gregory et al. (2016) developed a protocol to use the PiCUS 3 under difficult conditions and especially for tropical tree species with highly irregular trunk outlines that can cause aberrant tomograms. Espinosa et al. (2017) presented a segmentation methodology to identify defective regions in cross-section tomographic images obtained with an Arbotom device.

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Different inversion algorithms based on straight-ray propagation have been used in acoustic tomography. The cell-based back-projection algorithm split the polygon of sensors into cells and the slowness (reciprocal of velocity) of each cell was assumed constant (Divos and Divos, 2005). By using the elementary back-projection approximation, the slowness of each grid cell equals to the average of the line slowness values of lines intersecting the cell and the resolution is determined by the number of cells. Filtered back-projections can be used to perform an inverse transformation to obtain the slowness function from the time-of-flight (TOF) data by assuming the stress waves propagate in straight lines (Brancheriau et al., 2012). Feng et al. (2014) put forward an image reconstruction method that utilized an interpolation algorithm which estimated the velocity value of the unknown grid cells based on the site information of the known cells. Du et al. (2015) proposed an improved ellipse-based spatial interpolation method which could be used to estimate the velocity value of a grid cell by the elliptic affected zones corresponding to the nearby velocity rays and a velocity compensation method was applied to obtain more accurate input data for spatial interpolation because of the anisotropic property of trees.

Li et al. (2014) investigated the stress wave velocity patterns in cross sections of black cherry trees and developed an analytical model of stress wave velocity in healthy trees. Their theoretical analysis indicated that the ratio of tangential velocity to radial velocity approximated a parabolic curve with symmetric axis $h = 0$ (h is the angle between tangential direction and radial direction). The experimental results of the sound cross sections showed that the measured velocity patterns were in good agreement with the theoretical analysis. The tomograms of the cross sections with internal decay reflected the anomaly of velocity pattern and the proposed theoretical velocity model can be used as a diagnostic tool to detect internal decay of live trees.

However, with the existence of cavity or other structural defects, the propagation path of acoustic waves may be altered, that is, the waves may not propagate along a straight ray and the transmitting ray from the source sensor may be curved by bypassing the defect to reach the receiver sensor. A wave propagating model based on curved rays can more closely reflect the true condition of a tree, thus allowing a better simulation of acoustic wave transmission.

Acoustic wave may propagate along curved path through a heterogeneous medium, and the curved-ray propagation model has been employed in many fields. The U.S. Bureau of Mines' (USBM) second generation tomographic program, BOMCRATR, performs curved-ray calculations using the shooting method which find the path to a particular receiver by tracing rays with different takeoff angles from the source and interpolating until one passes sufficiently close to the receiver (Tweeton, 1992). The third-generation USBM tomographic program, MIGRATOM, uses a modeling migration of a continuous wavefront to address various mining-related problems by reconstructing the velocity distribution in the rock mass. MIGRATOM has been proved effective with both synthetic and field data sets (Jackson and Tweeton, 1994).

In tomographic imaging, the mathematical nonuniqueness of the solutions is a critical problem that affects the reconstruction (Jackson, 1979; Jackson and Tweeton, 1994). The insufficient measured data or limited range of viewing angles results in singular matrices in the velocity inversion, because the travel-time equations are not all linearly independent and thus many solutions can be found to fit the data equally well. Simultaneous iterative reconstruction technique (SIRT) algorithm is a traditional image reconstruction method which can solve the sparse matrix problem. There are also some strategies for reducing the nonuniqueness. For example, constraints may be imposed on the solution and be incorporated into the inversion to limit the range of the possible solutions (Jackson and Tweeton, 1994; Socco et al., 2004).

To improve the accuracy and reliability of tomographic technique, we proposed an imaging method based on a hybrid wave propagation model (HWPM) to reconstruct acoustic tomographic images using the measured TOF data. The hybrid wave propagation model applied both straight-ray and curved-ray transmission models for iterative image reconstruction. The effectiveness of the hybrid inversion method was examined through actual multipath acoustic wave testing conducted on log samples and live trees.

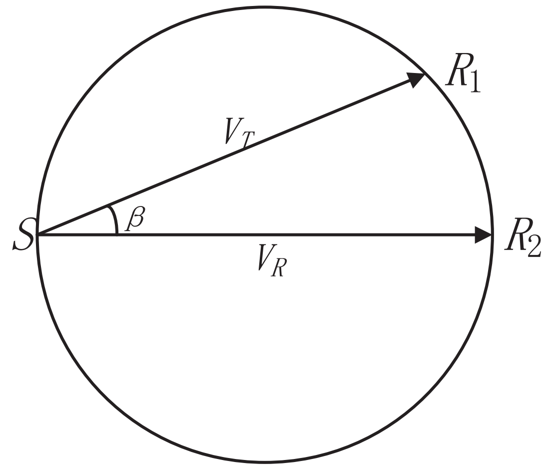

Fig. 1. Stress wave propagation in the cross-section of tree trunk.

2. Principle of tomographic imaging of live trees

2.1. Wave velocity pattern in sound healthy trees

A better understanding of wave velocity patterns in trees is important to develop reliable and effective imaging software for internal decay detection. For simplicity, we assume that the cross section of tree trunk is an ideal circularity (Fig. 1). In Fig. 1, S represents the source sensor, and R_1 and R_2 represents the receiver sensors. Stress waves propagate from the source sensor to the receiver sensors. SR_1 is the tangential direction, and SR_2 is the radial direction. V_T is the tangential wave velocity, V_R is the radial wave velocity, and β is the angle between radial direction and tangential direction. Generally, the stress wave velocity along radial direction is the largest and the velocity will decrease with the increment of the direction angle β. Li et al. (2014) presented an analytical model of the ratio of tangential velocity to radial velocity in sound trees, which approximates a second-order parabolic curve with respect to the symmetric axis $\beta = 0$ as following equation (1). Fig. 2 shows the wave velocity pattern of one sample tree. Here, the angle β was converted into radian unit ($1^\circ = \pi/180$). The relationship between velocity ratio V_T/V_R and angle β was statistically in a parabolic curve, with a coefficient of determination $R^2 = 0.9989$. The coefficients of the second order polynomial regression are $a = -0.2062$, $b = -0.0096$, and $c = 1.0067$. It was noted that the coefficient of the first order term was close to zero and the constant

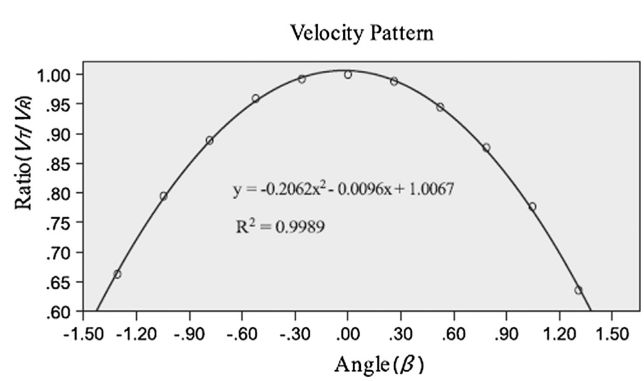

Fig. 2. Wave velocity pattern of sample trees.