Detection and Measurement of Internal Defects for Tree Trunk by GPR

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***Abstract* — Application of Ground Penetrating Radar (GPR) in tree trunk internal defects test is technically a Non-destructive Detection (NDT), especially suitable for the measurement of old and rare trees. The living trees complex internal structure makes the wooden medium highly anisotropic and heterogeneous. GPR uses the principle of the scattering of the electromagnetic wave which propagates through the medium and is reflected from object. The velocity of the scatter signal is determined primarily by the permittivity of the material which is influenced by water content and density. For rising the precision of NDT to old willow internal detects, in our investigation, we analyse the model of relationship between the dielectric constant and the moisture content of the ancient willow, the model was used in maintenance experiment of ancient Salix babylonica at the Summer Palace Beijing China. The test results indicate that the precision of internal defects measurement can be improved to 5% by using the relationship model, without which the precision is beyond 10%.**

Keywords - Ground Penetrating Radar; Non-destructive detection; Ancient willow; Dielectric constant; Moisture content

I. INTRODUCTION

Due to the deterioration of the natural environment, a large amount of wild trees die by hollow or rot, leading to damage to the environment and ecologicall imbalance; Moreover ancient trees may die or become damaged due to hollow rot, insects, etc., Loss to the cultural heritagee. For the healthy growth of trees, and the conservation of ancient and famous trees timely, the technology and methods of wood internal NDT is particularly important. NDT technology has been introduced to timber detection for over 50 years. The most obvious feature is that it doesn't destroy the original characteristics of the material; furthermore, it conducts the expected results in a short time, so that the operator can make judgments promptly [1]. Visual method is the first used and easier method for NDT. The results are mainly determined by operator's experience, easily affected by human factors, which lowers the accuracy of judgement. It's impossible to take direct and precise measurement of the internal situation of wood. Stress wave method is followed by inaccuracy, internal defects invisibility and injury to measured object[2-4]. Ultrasonic inspection technique is susceptible to outside interference. When applied to online testing, it calls for further research to figure out how not detect effectively without reducing production efficiency [5-7]. Computerized tomography method is expensive and gives off radioactive elements. It could easily lead to detrimental consequences if used improperly. Ground penetrating radar (GPR) is a nondestructive detection technology using electromagnetic waves to detect the electrical characteristics of the medium, widely used in the field of shallow exploration, such as civil engineering, hydraulic engineering, field archeology and other fields. In recent years, GPR for trees detection also is gradually taken seriously by scholars. Research conducted by Anthony N.Mucciardi [8] applied for patent on non-invasive inspection of trees for internal decay based on GPR. Dayakar Devaru elaborated the advantages of GPR detection for trees and studied the algorithm for identifying the defects in wooden logs using GPR [9]. Udaya B. Halabe made use of GPR to detect the position of internal defects (knots, decays, embedded metals) of trees [10]. J. R. Butnor found that near-surface decay, air-filled voids could be successfully estimated by GPR and GPR had potential to detect defects in angiosperms [11]. R. Martínez-Sala made the assessment of the dielectric anisotropy in timber using the nondestructive GPR technique [12]. A study by Xihong Cui [13] has demonstrated Tree-Root biomass in different depths using Ground-Penetrating Radar. S. Razafindratsima's study showed the closed relations between relative permittivity and moisture content of the different wood samples and indicated GPR features in time domains present some correlations with moisture content of wood material [14]. V. Pérez-Gracia located the defect of wood beams in buildings with ground penetrating radar [15]. Kathryn Decker detected the laminated wood using GPR and found rotted wood had higher frequency content compared to intact wood [16]. In addition, H. Lorenzo has developed nondestructive wood analysis methods in living tree trunks and dry timber. He pointed out that these anomalies could be associated the inner discontinuities between the bark and the internal trunk and lower velocities correspond to living trees, while higher velocities are associated with timber. However, at present, most studies limit to the location of defects of trees and characteristics of electromagnetic wave propagation mechanism in trees. In this article, the relation of moisture content and dielectric constant of Salix babylonica was investigated, and applied in defect non-destructive detection for rising the precision of NDT to ancient willow internal detects. The method and experiment data analysis are also demonstrated as follow.

II. PRINCIPLE OF NDT FOR TREE TRUNK BY GPR

A. NDT Principle by GPR

Trees trunk radar detection principle originated from Ground-Penetrating Radar (GPR). The basic principle of tree radar is to use high-frequency electromagnetic wave (1M ~ 1GHz) fed into the wood in form of pulses, oriented through a transmitting antenna. During the radar wave propagation in the wood material, when encountered with decay or a hole with electrical differences, the electromagnetic wave is reflected back to the bark and received by the transmitting antenna. By processing and analyzing the received radar, we can infer trees defect location, structure, electrical properties and geometry, so as to carry out trees internal defects detection based on the received radar wave form, intensity, time, etc. Radar wave transmission path in wood and tree trunk test method are shown in Figure 1. When the radar wave is spreading in defective wood through different media (e.g. decay, holes, insects, etc.), the wave path and intensity will change correspondingly.

Radar wave velocity (V_p) is given as equation (1):

$$V_p = c / \sqrt{\varepsilon'} \tag{1}$$

ε' is the dielectric constant of the medium, c the velocity of electromagnetic waves in vacuum=300mm/ns , z is the depth of the target of interest(e.g. defects) and t the round-trip time. It can be inferred that radar wave velocity in wood is influenced by the dielectric constant of the wood, which is closely related to the moisture content of wood.

The depth (Z) from decay to interface is given as equation (2):

$$Z = \frac{c \times t}{2 \times \sqrt{\varepsilon'}} \tag{2}$$

In the case of electromagnetic waves under normal incidence, the amplitude reflection coefficient R is given by Equation (3), where the subscripts 1 and 2 denote the first and second media at the interface ε_1 and ε_2 are the dielectric constants of the two media.

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \tag{3}$$

According to Fresnel formula (3): (1)the difference of electromagnetic properties of the medium on both sides and the intensity of reflected wave is positively correlated, and the property of medium on both sides can be deduced by the amplitude of the reflected waves. (2) When waves transmit from low to high dielectric constant medium, the reflection coefficient is negative, that is, the amplitude of the reflected wave reverse. On the contrary, when waves transmit from high to low dielectric constant medium, the reflection coefficient is positive, that is, the amplitude of the reflected wave is in the same direction. For example, the amplitude of the reflected radar waves reverses from air into the trunk. In contrast, the amplitude of the reflected radar waves from cavity of tree is in the same direction with radar wave. The reflections from tree bark and the reflection from the hollow area are in opposite direction. Therefore, the amplitude and direction of radar reflected waves are the important bases for differentiating interfacial electronic properties of two sides.

B. Data Acquisition and Post-processing

In this experiment, the ancient Salix babylonica from the Summer Palace Beijing China was applied as experimental subjects. The height of the measured cross-section and the starting point was marked before processing. And then, radar took 360 degrees scan around the circumference of the tree at the height and the data was stored in field computer. The circumferential scanning tree trunk is shown in figure 1. In the end, radar scanning switched to a single point scanning mode, the radar placed in the front side of the trees, with the metal plate placed in the corresponding backside. In this way, most of radar waves were reflected when encountered a mental plate. Thus, the propagation velocity and the average dielectric constant of trees can be calculated by the two-way travel time in the known distance (diameter trees).

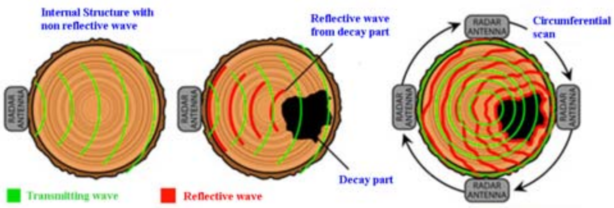

Fig. 1. Circumferential scanning wooden structure using radar wave

Radar signals are tend to attenuation and loss with increasing depth during the propagation of trees. The greater the signal loss is at deeper detection area. Thus, the echo data require dependent gain which compensates for amplitude reduction with depth. Prior to compensate for gain, in order to ensure that the mean of data is zero, the A-Scan data must remove the DC component, avoiding the obvious zero drift. Signal gain processing requires data with less noise, or the noise may be magnified. In addition, the attenuation of radar signals is low near the surface but very high towards the center of the logs due to high moisture in the center.

The echo data of radar requires noise filtering after zero correction. High-frequency noise, horizontal interference and direct coupling surface reflections need to be removed. The high frequency noise will result in "snow-like" noise in the data. When the range is set near the maximum limits for antenna or when large amount of gain is used, it often appears high-frequency noise.

Noise affects the judgement of reflective surface seriously. Noise can be removed by vertical high-pass filter and vertical low-pass filter. The horizontal interference signal has a low frequency characteristic, with a vertical high-pass filter do corresponding treatment. The cut–off frequency of vertical high pass filter usually is set to about 1/3 the center frequency of the antenna （1/3**Error! Reference source not found.** 900MHz=300MHz）. The low pass filter reduces the high frequency "snow-like" noise. The cut-off frequency of the vertical low pass filter is set at twice the center frequency of antenna（2**Error! Reference source not found.**900MHz=1800MHz）. It's necessary to stress that filtering also has shortage of adding unwanted

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signals and also removing desirable features from data. So one has to compare the unfiltered with filtered data during the analysis process. And adjust filter parameters as far as possible in the removal of radar clutter component of the original data and ambient noise signals, meanwhile, the echo signal without distortion. The above processing steps (amplitude gain, zero correction, noise filtering) were applied to all data.

In this article, post-processing were adopted is AGC, zero correction and FIR noise filtering, After post-processing was applied, the echo from the bottom of the log and some of the internal features became more obvious.

C. Detection Equipment and Its Limitation

The GPR system for the research is Tree Radar Detection System (Tree Radar, Inc. USA). Trees radar detection system can be divided into field data manager and radar antenna, as shown in Figure 2. Due to the significant different of moisture content among wood species under various conditions, the dielectric constant varies simultaneously. When in the actual measurement processing, radar detection system is assumed to propagate in a medium with the dielectric constant of 12.4, without considering different specimen of trees and environment. In our investigation, for improving the accuracy of detection result, we studied the relationship between the dielectric constant and moisture content of tree trunk, and using correcting permittivity for different testing respectively. The method was applied in field experiment for old Salix Babylonica at the summer palace.

Fig. 2. Filed Experiment at the Summer Palace, Beijing, China, using Tree radar system with 900MHz GPR antenna

III. ANALYSIS ON RELATIONSHIP BETWEEN THE PERMITTIVITY AND MOISTURE CONTENT OF WILLOW

The vast territory of forest resources and diverse climatic conditions in our country contribute to a wide variety of tree species. There are significant differences in relationship between the dielectric constant and moisture content among different species. Based on this fact, aimed at the decadent defects of ancient willow in the Summer Palace West Dyke, this article will focuses on the relationship model between dielectric constant and moisture content of ancient willow as an example. The method used in this paper is also applicable to radar NDT on other tree species.

A. Method and Materials

The ancient willow trunks adopted in this study are in the form of cylinders with a diameter of 32 mm and a height of 3mm. The directions of wood samples are made perpendicular to grain for mitigating its influence on test results. The samples are divided into 16 groups, each with 3 pieces. Then the follow steps were implemented gradually, and the result raw data was shown in table I.

The oven dried weight of the samples were taken by drying in an electronic oven at 100 ± 3 ℃ for 24 hours, denoted as m_1.

a) Placed each group of specimens in sealed glass vessels with different concentrations of sulfuric acid reagent for 72 hours.
b) Recorded the weight of this specimen as m_2 with weighing scales, and put the specimen back into the vessel.
c) Weighed the specimen again and recorded as m_3, then compared m_2 to m_3.
d) When m_2-m_3<0.01g, used a LCR meter to measure the dielectric constant of specimen; when m_2-m_3>0.01g, repeated steps c and d until met m_2-m_3<0.01g.

TABLE I. RESULT DATA TO RELATION OF MOISTURE CONTENT WITH DIELECTRIC CONSTANT

No.	moisture content ω	dielectric constant ε
1.	0.0985	1.0357
2.	0.2015	2.3654
3.	0.2911	2.3727
4.	0.4067	2.4684
5.	0.5089	2.4715
6.	0.5899	2.5465
7.	0.6931	2.9974
8.	0.8073	3.1272
9.	0.8975	3.1141
10.	0.9821	3.7543
11.	1.0982	4.2713
12.	1.1949	4.6972
13.	1.3078	7.6429
14.	1.3981	7.7181
15.	1.5045	11.9782
16.	1.6155	12.1521

B. Analysis of result data

PASW Statistics software was carried out on the test data processing. First of all, the significance level analysis result is: sig. = 0.000. It shows there is a significant difference in moisture content and dielectric constant. Therefore, the data could be processed through curve fitting method. The result was shown in table II and figure 3.

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TABLE. II.CURVE FITTING PARAMETER ESTIMATION FOR RELATION MODEL

Equation	The Model Summary					Parameter Estimation			
	R^2	F	df_1	df_2	Sig	b_0	b_1	b_2	b_3
linear	0.765	45.62	1	14	0	-.627	6.23	/	/
secondary	0.937	96.58	2	13	0	3.028	-5.88	7.09	/
cubic	0.968	122.1	3	12	0	.815	7.699	-12.2	7.52
growth	0.896	120.7	1	14	0	.219	1.305	/	/

In Table II, R^2 is the curve fitting degree, indicating the similarity of fitting curve to sample curve. F value indicates a significant degree of R^2. Sig. is significance. Parameter estimation of b_0, b_1, b_2, b_3 is equation coefficient respectively, shown in the equation (4):

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 \tag{4}$$

The highest fitting (R^2) is cubic curve, R^2 is 0.968. Therefore, cubic curve's fitting level is the best. The relationship between the dielectric constant and moisture content of willow equation is shown in eq. (5):

$$\varepsilon = 0.815 + 7.699\omega - 12.201\omega^2 + 7.520\omega^3 \tag{5}$$

Where ε is the dielectric constant, ω is the moisture content.

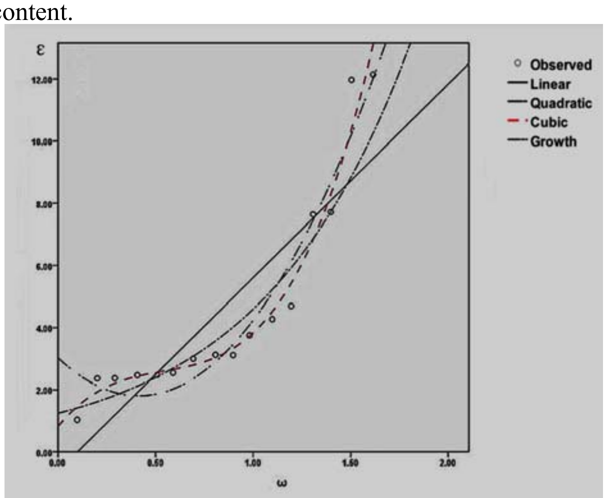


Fig. 3. Curve fitting the relation with different curve method

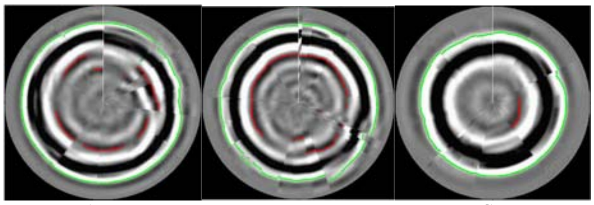
The cubic curve in the figure 3 indicates that the dielectric constant increases as the moisture content increases from 0 to 25%. The moisture content from 25% to 100% does not have much effect on the dielectric constant. The abrupt change of the dielectric properties is observed at very high moisture content and the curve becomes concave upward.

IV. APPLICATION IN OLD SALIX BABYLONICA INTERNAL DECAY DETECTION

Select the ancient willow trunks with different levels of defects from the Summer Palace for test specimens, as shown in Figure 4. While Use trees radar detection systems to scan ancient willow trunks, the test results are shown below in Figure 5.

A B C

Fig. 4. Selected willow trunk specimens with different levels of defects, A is 1# B is 2# C is 3#



A B C

Fig. 5. Gray scale detection of selected specimens, A is 1# B is 2# C is 3#

As can be seen from the figure 4 and figure5， the profile of willow specimens are irregular. For comparing the difference between the test results and the actual defect, grid CAD method which is shown in figure 6, was adopted to calculate the ratio of detect area to the total area. The finer the mesh is, the more accurate the area is. In this paper, the accuracy of a grid is 1 millimeter.

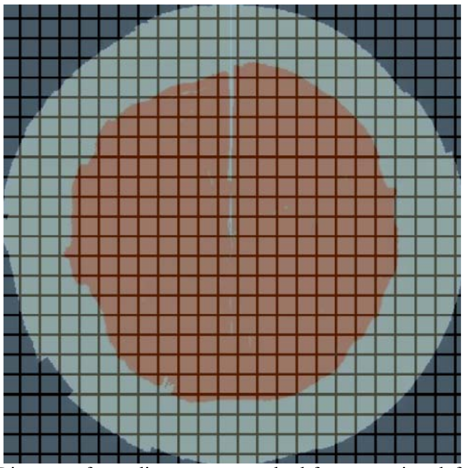
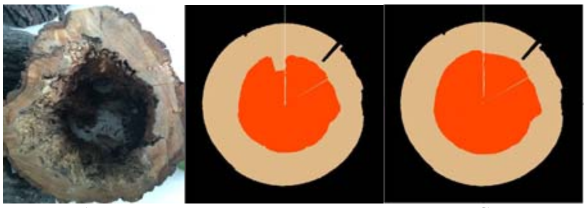


Fig. 6. Diagram of coordinate paper method for measuring defect area, 314 grids is decay area shown in red and 803 grids is total area of trunk; radio of decay area to trunk area is 39.1%

A. *Analysis of the 1# specimen*



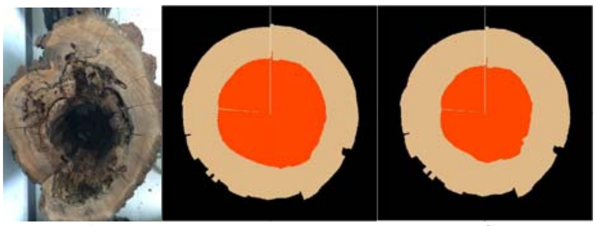
A B C

Fig. 6. Compared result of actual defect (shown in A) with detected defect without model correction (shown in B) and with model correction (shown in C) for 1# specimen

In figure 6, A is the actual defects photo of ancient willow trunks from 1# specimen, with the defect area of 0.0830m2 measured by coordinate paper method. Figure 7 is the result from tree radar detection system by using analysis software, given a specific dielectric constant. Defect area calculated in CAD method is 0.0754m2. Compared with actual defects, the measurement error is 9.15%.

The error is originated from the influence of moisture content on dielectric constant as we mentioned before. We need accurate measurement of the moisture content of the branches, and the previous relationship model between moisture content and dielectric constant to calculate willow's dielectric constant. In this way the trees radar system can carry out a precise defect graphic under an analysis condition similar to actual environment. During the test the moisture content of the willow trunks is 165%, so that the dielectric constant is 14, and the final analysis is shown in B of Figure 7. C of Figure 7 is the measurement result by relationship model, with a defect area of 0.0854m2 by CAD method. The measurement error is about 2.9%. therefore radar detection precision has risen after data processing.

B. *Analysis of the 2# specimen*

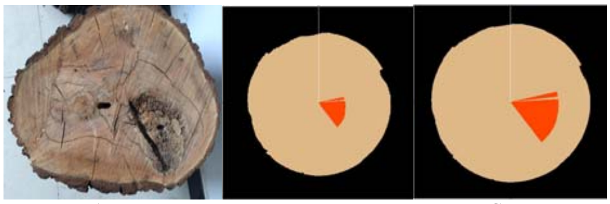


A B C

Fig. 7. Compared result of actual defect (shown in A) with detected defect without model correction (shown in B) and with model correction (shown in C) for 2# specimen

In figure 7, A is the actual defects photo of ancient willow trunks from second group, with the defect area of 0.0894m^2 measured by coordinate paper method. Figure 11 is the result from tree radar detection system by using analysis software, given a specific dielectric constant. Defect area calculated in CAD method is 0.0961m^2. Compared with actual defects, the measurement error is 7.38%. The moisture content of the willow trunks is 144%, and the dielectric constant is 9, as the final analysis shows in B of Figure 8. C of Figure 8 is the result by using relationship model parameters. Defect area calculated in CAD method is 0.0854m^2. Compared with actual defects, the measurement error is about 4.5%. Therefore radar detection precision has risen after data processing.

C. *Analysis of the 3# specimen*



A B C

Fig. 8. Compared result of actual defect (shown in A) with detected defect without model correction (shown in B) and with model correction (shown in C) for 2# specimen

In figure 8, A is the actual defects photo of ancient willow trunks from third group, with the defect area of 0.0043m^2 measured by coordinate paper method. Figure 15 is the result from tree radar detection system by using analysis software, given a specific dielectric constant. Defect area calculated in CAD method is 0.0038m^2. Compared with actual defects, the measurement error is 11.62%. The moisture content of the willow trunks is 144%, and the dielectric constant is 9, as the final analysis shows in B of Figure 9. C of Figure 9 is the result by using relationship model parameters. Defect area calculated in CAD method is 0.0045m^2. Compared with actual defects, the measurement error is about 4.6%. Radar detection precision has risen after data processing.

V. CONCLUSION AND DISCUSSION

Limited by traditional testing methods, internal defects detection of trees and ancient wooden beams failed to be non-destructive. The difference between wood NDT radar technology and ground-penetrating radar is the incapability of constructing a unified test model due to high moisture content, which varies significantly in different species under different conditions. In this paper, we applied trees radar detection system and used moisture calibration method to construct the relationship model between dielectric constant and moisture content of ancient willow. Using this model we correct the dielectric constant of ancient willow and apply it to the internal defect detection of willow specimens. Experimental results show that, by correction coefficient method, detection accuracy will increase from about 10% to less than 5%, thus effectively improve tree NDT radar precision and reliability of test results. The method used in this paper is also applicable to radar NDT on other tree species.

Although NDT radar wave technology has made some progress in defect detection of ancient wood, but in practical measurement there are still several problems:

(1) The specimens selected for this test are hollow decadent ancient willow, while for the change in moisture

content of living trees we need a more accurate moisture content detecting device for calibration.

(2) Existing trees radar detection system in the actual measurement has hardware and software limitations, inevitably lead to bias and loss of data. Therefore we need further research on hardware and software modificationn to improve the accuracy of the test.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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