Research on the relationship between moisture content and the dielectric constant of the tree trunk by the radar wave

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Abstract

Radar wave technology offers a noninvasive, quick determination technique and has potential for the applications of the non-destructive detection (NDT) for the trees trunk and wood based materials. The precision of NDT determination by radar wave is influenced the wood dielectric constant which is closely related to the moisture content of the trees trunk. For our investigations we used TRU trees radar wave to detect the trees trunk. Four typical trees trunks were selected: polar, willow, pine, eucalyptus. Different trees trunks moisture content and dielectric constant were tested under the radar wave frequency respectively. Models of the relationship between moisture content and dielectric constant of the trees trunks were established for improving the accurate of radar wave NDT.

Keywords: radar wave, dielectric constant, moisture content, tree trunk, non-destructive detection

1 Introduction

As a new detection technology, Radar wave NDT has been widely applied in geological exploration. Electromagnetic wave signal was first used in detection of underground metal body by German Hulsmeyer. In 1910, Leimback and Lowy proposed radar's principles to ground-penetrating in the form of patents, it was the first time that the concept of ground penetrating radar (GPR) was put forward formally [1, 2]. In the early 1970 s, Domestic began the study of ground penetrating radar (GPR) and gradually applied to engineering application [2, 3]. In the early 1990 s, the technology was gradually widely used in many fields such as engineering geology exploration, quality inspection, mine detection, disaster geology survey, archaeological investigation, exploration, non-destructive evaluation [4]. In 2009, J R Butnor [5] etc. applied GPR technology to pinaceae standing timber, and the detection result was compared with hardwood. The TRU trees radar was developed by Tree Radar Company in the USA for wood internal defects detection. It was the first time the Radar wave was applied in the tree trunk NDT commercial application. Due to the fixed electric constant value of the TRU radar system, limited precision and poor suitability have limited its development and application in tree trunk NDT. Many experiment results showed that the detect result of wood internal defects changed by selected dielectric constants. And the moisture content has a great influence on the dielectric constant [6, 7]. Thus, it can be seen that the detecting precision of the defects is closely related to the dielectric constant of the measured wood, and wood moisture content is the key factor of dielectric constant of the wood. Therefore, in this paper, the different relationship of four typical woods such as poplar, willow, pine and eucalyptus between dielectric constant and moisture content were studied respectively.

2 Material and methods

The four kinds of typical wood adopted in this study are newly felled. It is reported that the dielectric properties of wood are related to wood structure, grain direction, moisture content, temperature, magnetic field frequency [8-10]. So, the radar detection system with a constant frequency of 900 MHz was used to investigate the dielectric properties at room temperature. Wood samples were in the form of cylinders with a diameter of 32 mm and a height of 3.0-3.5mm, in addition, the two main directions of wood samples were considered – parallel to grain and perpendicular to grain.

The dielectric constants were carried out by a Precision Impedance Analyser (Agilent 4294A) shown in Figure 1. Tree Radar Company's TRU radar equipment was used in this study shown in Figure 2.

FIGURE 1 Precision Impedance Analyser

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FIGURE 2 Field data manager and the radar antenna

Samples were placed under different moisture conditions for 96 hours.

The weight of the samples were measured respectively before and after each measurement of dielectric constant, denoted as w1 and w2. Dielectric constant values were measured at room temperature under the frequency of 900 MHz, denoted as ε.

After the test, samples were placed in the air.

Repeated step 1~2 until the weight had no significant change.

Finally the oven dried weight of the specimens was taken by drying in an electronic oven at 100 ± 3°C for 24 hours.

PASW Statistics software was carried out on the test data processing [11].

3 Results and discussion

First of all, the significance level of four groups' data was analysed respectively, the all result: 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.

R^2 is the curve fitting degree. That is how many percent of your sample curve similar. *F* value indicates a significant degree of R^2. *Sig*. is significant, the closer to 0.000, the better. Parameter estimation of b_0, b_1, b_2, b_3 is equation coefficient respectively:

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 . \quad (1)$$

Equation's inspection level α is 0.001, the value of sig. was 0.000. Four equations of poplar are significant. The highest fitting (R^2) is cubic curve, R^2 is 0.973. Therefore, cubic curve's fitting level is the best. The relationship between the dielectric constant and moisture content of poplar equation is:

$$\varepsilon = -0.351 + 14.994\omega - 19.475\omega^2 + 9.543\omega^3 , \quad (2)$$

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

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.

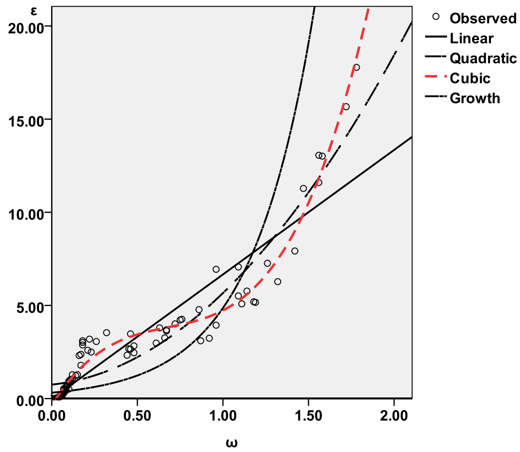

FIGURE 3 Curve fitting poplar moisture and dielectric constant

The various parameters in Tables 2 and 1 are the same. Equation's inspection level α is 0.001, the value of *Sig*. is 0.000. Four equations of willow are significant. The highest fitting (R^2) is cubic curve, R^2 is 0.964. Therefore, cubic curve's fitting level is the best. The relationship equation between the dielectric constant and moisture content of willow is:

$$\varepsilon = -0.132 + 13.738\omega - 22.307\omega^2 + 11.638\omega^3 , \quad (3)$$

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

TABLE 1 Popular model and parameter estimation

Equation	The Model Summary					Parameter Estimation			
	R^2	F	df_1	df_2	*Sig.*	b_0	b_1	b_2	b_3
linear	.868	597.189	1	91	.000	.029	6.755		
secondary	.913	474.960	2	90	.000	.755	1.412	3.650	
cubic	.973	1066.237	3	89	.000	–.351	14.994	–19.475	9.543
growth	.525	100.572	1	91	.000	–1.065	2.680		

TABLE 2 Willow model and parameter estimation

equation	The model summary					Parameter estimation			
	R^2	F	df_1	df_2	*Sig.*	b_0	b_1	b_2	b_3
linear	.711	201.997	1	82	.000	.386	4.345		
secondary	.817	180.651	2	81	.000	1.111	–.681	3.885	
cubic	.964	705.922	3	80	.000	–.132	13.738	–22.307	11.638
growth	.428	61.370	1	82	.000	–.715	2.228		

ω is the independent variables, ε is the dependent variable.

From cubic curve in the Figure 4 we can see, the dielectric constant increases as the moisture content increases from 0 to 20% the moisture content from 20% to 100% does not have much effect on the dielectric constant. The abrupt change of the dielectric properties are observed at very high moisture content and the curve becomes concave upward.

The various parameters in Tables 3 and 1 are the same. Equation's inspection level α is 0.001, the value of *Sig.* is 0.000. Four equations of pine are significant. But the curve fitting is not very good. R^2 is only 0.803, according to the law of the scatter distribution, piecewise fitting, depending on the moisture content of pine, is divided into below 25% and above 25%.

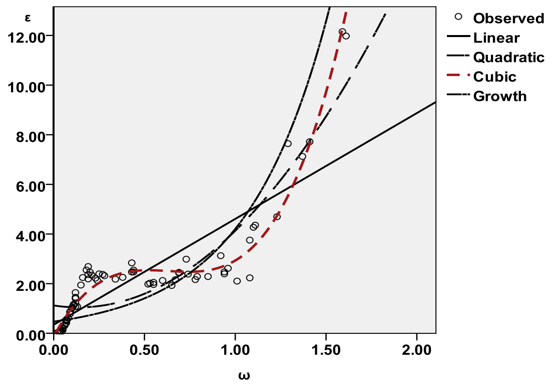

FIGURE 4 Curve fitting willow moisture and dielectric constant

TABLE 3 Pine model and parameter estimation

equation	The model summary					parameter estimation			
	R^2	F	df_1	df_2	*Sig.*	b_0	b_1	b_2	b_3
linear	.803	374.050	1	92	.000	.168	8.269		
secondary	.803	185.196	2	91	.000	.114	8.641	–.312	
cubic	.803	122.365	3	90	.000	.219	7.394	2.174	–1.223
growth	.528	102.908	1	92	.000	–.907	3.316		

ω is the independent variables, ε is the dependent variable.

TABLE 4 Pine model and parameter estimation(below 25%)

equation	The model summary					parameter estimation			
	R^2	F	df_1	df_2	*Sig.*	b_0	b_1	b_2	b_3
linear	.926	597.056	1	48	.000	–1.012	20.508		
secondary	.957	528.419	2	47	.000	–.346	6.297	58.053	
cubic	.967	451.443	3	46	.000	.101	–10.791	225.962	–455.280
growth	.823	222.439	1	48	.000	–3.408	25.786		

ω is the independent variables, ε is the dependent variable

The various parameters in Tables 4 and 1 are the same. Equation's inspection level α is 0.001, the value of *Sig.* is 0.000. Four equations of pine are significant. The highest fitting (R^2) is cubic curve, R^2 is 0.967. Therefore, cubic curve's fitting level is the best. The relationship equation between the dielectric constant and moisture content of pine (Figure 5 below 25%) is:

$$\varepsilon = 0.101 - 10.791\omega + 225.962\omega^2 - 455.280\omega^3 . \quad (4)$$

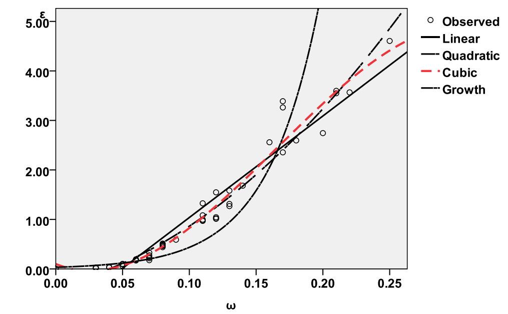

FIGURE 5 Curve fitting pine moisture and dielectric constant

The various parameters in Tables 5 and 1 are the same. Equation's inspection level α is 0.001, the value of *Sig*. is 0.000. Four equations of pine are significant. The highest fitting (R^2) is cubic curve, R^2 is 0.950. Therefore, cubic curve's fitting level is the best. The relationship equation between the dielectric constant and moisture content of pine (Figure 6 above 25%) is:

$$\varepsilon = 11.727\text{-}45.725\omega + 72.995\omega^2\text{-}29.178\omega^3. \quad (5)$$

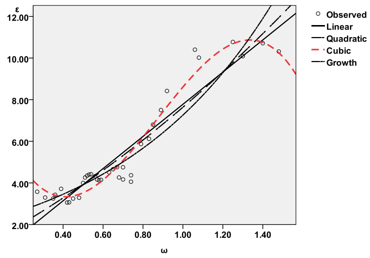

FIGURE 6 Curve fitting pine moisture and dielectric constant

TABLE 5 Pine model and parameter estimation (above 25%)

equation	The model summary					parameter estimation			
	R^2	F	df_1	df_2	Sig.	b_0	b_1	b_2	b_3
linear	.842	207.991	1	39	.000	.200	8.248		
secondary	.843	102.196	2	38	.000	–.306	9.755	–.914	
cubic	.950	235.228	3	37	.000	11.727	–45.725	72.995	–29.178
growth	.857	232.948	1	39	.000	.770	1.291		

ω is the independent variables, ε is the dependent variable

The various parameters in Tables 6 and 1 are the same. Equation's inspection level α is 0.001, the value of *Sig*. is 0.000. Four equations of Eucalyptus are significant. The highest fitting (R^2) is cubic curve, R^2 is 0.951. Therefore, cubic curve's fitting level is the best. The relationship equation between the dielectric constant and moisture content of Eucalyptus is:

$$\varepsilon = -0.365 + 9.426\omega + 10.976\omega^2 - 15.777\omega^3. \quad (6)$$

TABLE 6 Eucalyptus model and parameter estimation

equation	The model summary					parameter estimation			
	R2	*F*	*df1*	*df2*	*Sig.*	*b0*	*b1*	*b2*	*b3*
linear	.945	1277.662	1	75	.000	–.343	10.791		
secondary	.949	692.827	2	74	.000	–.634	13.658	–4.682	
cubic	.951	469.925	3	73	.000	–.365	9.426	10.976	–15.777
growth	.738	211.522	1	75	.000	–1.108	5.957		

ω is the independent variables, ε is the dependent variable.

Pine overall fitting curve is shown in Figure 7. By the fitting degree of R^2, the piecewise fitting degree of pine is larger than the whole. So we choose the sub-fitting equation.

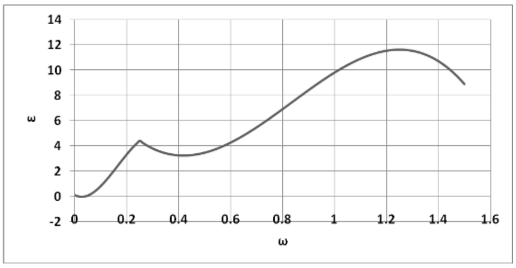

FIGURE 7 Curve fitting pine moisture and dielectric constant

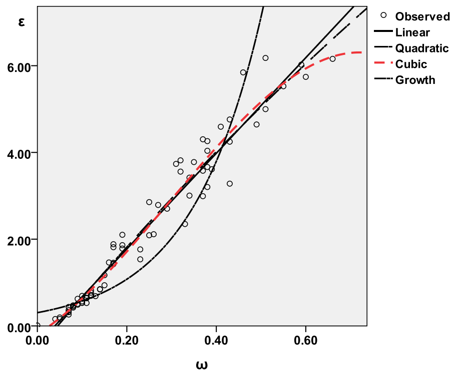

FIGURE 8 Curve fitting eucalyptus moisture and dielectric constant

From cubic curve in the Figure 8 we can see, the dielectric constant increases as the moisture content increases from 0 to 65%.

The main work of this paper is to use the TRU trees radar system to achieve accurate measurement of timber internal defects. Because in the measurement process of intermediary the radar system's electric constant value is fixed, the system exists accuracy defects. The results show that if different dielectric constants can be chosen, the location of detected wood internal defects is different. And as the moisture content of lumber changes, its dielectric constant changes.

According to the dielectric constant values of wood at different moisture content obtained in this paper, taking pine as an example, the results of analysis are applied. A piece of pine whose moisture content is 100% was chosen. A hole is measured in 10.5 cm from the bark. The defect position was gotten with TRU trees radar system, as shown in Figure 8. When the moisture content is over 25%, the pine's dielectric constant is obtained by this article. The relationship equation:

$$\varepsilon = 11.727 - 45.725\omega + 72.995\omega^2 - 29.178\omega^3. \quad (7)$$

If the moisture content is 100%, the dielectric constant is 9.819. The permittivity of TRU trees radar detection system was corrected to 9.819, measured defect location again, as shown in Figure 9. Compare Figure 8 to Figure 9, defect location in Figure 8 is 9.5 cm, error is about 9.5%. But defect location in Figure 10 is 10.7 cm, error is about 1.9%. Therefore, the measurement position using the model was closer to the actual position of a defect. It was found that application of the model has improved the accuracy of the TRU trees radar system.

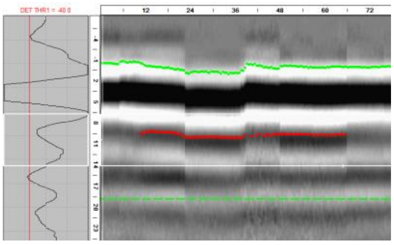

FIGURE 9 defect locations of pine

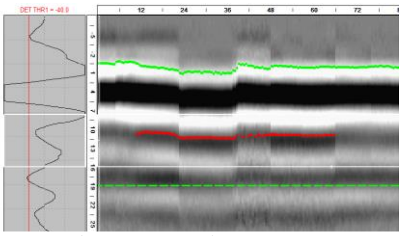

FIGURE 10 defect locations of pine application model

4 Conclusions

Relational models of four typical wood moisture content and dielectric constant were obtained, by the dielectric constant measuring instrument and the weighing method. The result shows that, for poplar, willow, eucalyptus, distribution curves of the relation between moisture content and dielectric constant were cubic, but for Pine, distribution curve was piecewise fitted with two different cubic. The dielectric constant increases exponentially with increasing the moisture content from 0 to Fiber saturation point (FSP), while it does not have much effect within the range of FSP to 100%, the concussion of measurement point was caused by measurement errors. When the moisture content is over 100%, the dielectric constant increases a bit linear upward trend.

Therefore, based on the relational model of moisture content and dielectric constant obtained, the accuracy of measurement instrument has been improved, meanwhile, experimental results showed that the model can improve the accuracy of the instrument effectively.

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