Microwave Non-destructive Testing of Wood Anisotropy and Scatter

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Abstract- A microwave Focused Beam transmission measurement is identified as a good candidate for fast, accurate and affordable industrial wood testing. In this paper, the transmission measurement setup, in its various forms, is applied to the measurement of wood properties, considering wood as an anisotropic, heterogeneous, multiphase dielectric. The depolarization of a linearly polarized plane wave in an anisotropic media is considered first. It is used for grain angle detection for arbitrary grain inclination in three-dimensional space. A good correlation with visually inspected grain angle values is obtained. A scattering experiment is performed, measuring the transmission through the wood when the transmitting and the receiving antenna axes are at the right angle. The results indicate that the annual ring arrangement strongly influences the scattering in the sideways direction, while other investigated parameters (defects, gradual density variation, bulk density) show poor correlation with measured scattering coefficient.

Keywords: Microwave measurement, Microwave propagation, Nondestructive testing, Wood industry, Free-space method.

I. INTRODUCTION

The permittivity of wood, measured at a certain frequency and temperature, strongly depends on moisture content and density. The effective permittivity is affected by the presence of defects such as knots and wood degradations. In addition, wood is strongly anisotropic, both in its physical strength and its electrical properties. Wood anisotropy is commonly described using vectors aligned with its principal directions: axial, radial and tangential. The axial direction is aligned with the vertical axis of the log and is referred to as 'parallel to' ($\parallel$) or 'along the' wood grain. The radial and tangential directions, related to the annual rings, have approximately equal permittivity value and are collectively referred to as a permittivity 'perpendicular to' or 'across the' grain ($\perp$). Description of wood anatomy can be found in the works of Ross and Pellerin [1], while the dielectric properties of wood are extensively treated in a book by Torgovnikov [2].

In this paper, we investigate the use of Focused Beam sensors in various arrangements around the sample, providing more information about wood's complex structure than is customarily available. In one aspect, this maximizes the number of independent parameters and improves the accuracy of derived empirical models. In general, it provides a better insight into the wave behavior in this complex media.

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Two novel sensor arrangements, tailored for detection of particular wood properties, are considered here.

The first arrangement consists of four antennas surrounding the sample, measuring the transmission in two orthogonal directions, and using wave polarization to investigate the anisotropy. The second arrangement presented here allows measurement of the scattering in the sideways direction. This study is not reported in the literature to date and it brings further insight in wave propagation through wood.

The motivation for wood anisotropy study comes from its potential application for grain direction determination. Wood grain is a pattern determined by the orientation of wood fibers, formed during the growth of a tree. The grain forms a mild helix in the axial direction, with an inclination which depends on the number of annual rings within the radius. The grain angle in wood is defined as the angle between the wood fiber direction and the vector in axial direction. Large grain angles can reduce the stiffness and shape stability of sawn timber. Shen and Schajer report [3] that the stiffness of wood along the grain is about twenty times higher than across the grain.

The first practical grain angle detection methods were reported in 1980's, with most significant work presented by King, James and Yen [4], who used a Modulated Scattering Technique. An alternative was invented by Heikkila [5], who measured the slope of grain using the ratio of two received voltages, measured in different polarizations. A method using Focused Beam Antenna System is presented by Malik et al. [6], who related the grain angle to the properties of the polarization ellipse of the depolarized transmitted wave. A significant contribution was made by Shen, Schajer and Parker [3], who detected a depolarization of the wave transmitted through the wood using a stationary modulated scatterer. This work was further advanced by Schajer and Orhan [7]. Depolarization and transmission were measured using all combinations of two orthogonal linear polarizations, which allowed determination of the grain direction. All reported studies deal with grain inclination in a plane, describing it with a single inclination angle θ .

The grain angle determination method, presented in this paper, builds on the reported studies, most notably the work of Schajer and Orhan [7]. However, while a resonant scattering technique is used in [7], this paper employs a Focused Beam system which allows bulk material testing within a volume illuminated by the beam [8,9]. Furthermore, three-dimensional anisotropy is considered. The second part of this paper considers scattering from the sample, correlating obtained results with wood features. Since both experiments use the same sensor and the set of equipment, the measurement setup

for both is presented in Section II. The results for the anisotropy and scattering experiments are then presented in separate sections.

II. MEASUREMENT SETUP

A. Anisotropy Measurement Setup

Anisotropy of wood causes a depolarization of a linearly polarized transmitted wave when the grain direction is neither aligned nor orthogonal to the wave polarization direction. The direction of the wood grain is related to the depolarization of the plane wave [8].

To determine the depolarization, the transmission of a linearly polarized wave in nominal and orthogonal polarizations was measured using a setup schematically presented in Fig. 1. The transmitting and receiving antennas were standard rectangular horns operating over the 8 to 12.4 GHz frequency range. A pair of 18 cm wide plano-convex dielectric lenses, mounted back to back, were positioned in front of the transmitting antenna, focusing the beam to a 6 cm spot at the focal distance of 17 cm. The lenses are made of paraffin ($\epsilon_r = 2.3$) and produce a converging beam, which allows wave interaction with the relatively small volume of the sample. This, further, minimizes scattering from surrounding objects and diffraction from sample edges.

Fig. 1 Measurement setup

Diffraction effects at the edges of the sample are negligible only if the minimum transverse dimension of the sample is greater than three times the beam-waist width illuminating it. However, samples used in this experiment were not sufficiently wide to prevent diffraction effects, having dimensions 10 x 5 cm only (standard 4"x2" lumber). Thus,

samples were positioned between two microwave absorbers, as shown in Fig. 2. The sample was positioned vertically at the focal distance from the lens and centre of the beam illuminates the spot at a height of 24 cm. Propagation through the sample was measured from two orthogonal directions. This allows determination of grain direction in three-dimensional space, as demonstrated in the following section. Measurements are performed using an Agilent PNA-L Network Analyzer N5230A, after a full two-port calibration.

Fig. 2 Implementation of transmission measurement setup for anisotropy measurement experiment

The change of antenna polarization can be achieved by either rotating a linearly polarized antenna or using a switchable, dual linearly polarized antenna. The transmission measurements in nominal and orthogonal polarization were performed using two antennas with aligned and orthogonal polarizations, respectively. In following text, the letter V is used to mark vertical polarization and the letter H horizontal polarization of the antenna, while polarization combinations of receiving and transmitting antenna are marked as VV, VH, HV and HH.

B. Scattering Measurement Setup

The measurement setup presented in Fig.1 is used for scattering measurements as well, but this time the transmission is measured not only to the receiving antenna on the opposite side of the sample but to the neighboring antenna as well. The two parameters describing the transmission are defined as the transmission coefficient S_{12} and the scattering coefficient S_{13} . The coefficient S_{12} is measured as a dB value of the transmission S parameter magnitude on the Network Analyzer, using a transmitting antenna Tx1 and a receiving antenna Rx1 (Fig. 1). The scattering coefficient S_{13} is measured in the same way, but this time as a transmission from antenna Tx1 to the receiving antenna Rx2. After each measurement, the sample is rotated around the vertical axis by 90° , so that every time a different sample side faces the transmitting antenna. This is indicated with an arrow at the base of the sample in Fig. 1. Letters f , b , l and r , (standing for front, back, left and right, respectively) are used in following text to indicate which sample side is facing the transmitting antenna for the presented set of results, with side f facing the transmitting antenna Tx1.

III. MICROWAVE ANISOTROPY MEASUREMENT

The depolarization of a linearly polarized plane wave propagating through anisotropic media is depicted in Fig. 3, for a simplified case, where the grain lies in a plane parallel to the wave front. When the polarization of an incident wave E_I is aligned with a principal direction of the media, the transmitted wave E_T remains linearly polarized (Fig. 3a). However, when the polarization is not parallel to principal directions of the anisotropic media, a depolarization occurs and transmitted wave E_T is elliptically polarized.

Fig. 3 Grain angle and wave depolarisation for (a) aligned (b) not aligned polarisation of the wave.

The transmission coefficient, defined as the ratio of transmitted and incident linearly polarized waves, is commonly used in microwave engineering [10]. For isotropic media, it is a complex quantity whose magnitude shows an attenuation of the wave and whose phase indicates the velocity of propagation through the media, while both incident and transmitted waves propagate in the same polarization. To describe the polarization purity of the propagating wave, we extend the commonly used definition and define a cross polar transmission coefficient as the ratio of linearly polarized transmitted and incident waves in two orthogonal planes.

The magnitude of the incident plane wave perpendicular to the grain direction is E_{I1} , while the magnitude in the grain direction is E_{I2} . The transmitted waves are E_{T1} and E_{T2} and the relationship between incident and transmitted fields is given by:

$$\begin{bmatrix} E_{T1} \\ E_{T2} \end{bmatrix} = \begin{bmatrix} R_H & 0 \\ 0 & R_V \end{bmatrix} \begin{bmatrix} E_{I1} \\ E_{I2} \end{bmatrix} = \mathbf{R} \begin{bmatrix} E_{I1} \\ E_{I2} \end{bmatrix} \quad 1$$

The transmission matrix $\mathbf{R}$ is diagonal and zero off-diagonal elements indicate the absence of depolarization. If the polarization directions don't coincide with principal directions, a depolarization occurs and transmission matrix is no longer diagonal. This new matrix $\mathbf{R}$ is now given by:

$$\begin{bmatrix} E_{T1} \\ E_{T2} \end{bmatrix} = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix} \begin{bmatrix} E_{I1} \\ E_{I2} \end{bmatrix} \quad 2$$

Experiments show that depolarization can be characterized using magnitudes only [8], which significantly simplifies the

problem at hand, since practical sensor implementation is more economical. Thus, $\mathbf{R}$ is considered to be real, containing transmission coefficient magnitudes only.

Fig. 4 Sample holder for the angle of depolarisation experiment

A. Relating transmission matrix with grain angle inclination

The following experiment demonstrates the relation between the grain angle and the amount of depolarization, i.e. the cross polar level magnitude. It is very hard to measure the anisotropy in an isolated manner, since different density and moisture contents of a sample influence the measurement outcome as well. In order to observe the effects of the grain angle only, we have measured the propagation through a single sample, inclining it at different angles, thus simulating a change in the grain angle inclination. A simple sample holder was constructed, shown in Fig. 4.

Fig. 5 Modelled and measured cross polar transmission coefficient magnitudes for Sample 1(S1) and Sample 2 (S2)

For simplicity, the two-dimensional anisotropy is considered, observing the axial direction as 'along the grain' and the radial direction as 'perpendicular to grain'. Magnitudes of all four transmission coefficients, measured at

seven inclination angles (0°, 15°, 30°, 45°, 60°, 75° and 90°) are given in Fig. 5 and 6.

Fig. 6 Modelled and measured nominal transmission coefficient magnitudes for Sample 1

The cross polar transmission shows that depolarization depends on the grain inclination angle θ , while a graph fitted through measured data (Fig. 5) indicates that depolarization is proportional to $\sin(2\theta)$. Two nominal polarizations (Fig. 6) are proportional to function $\cos(2\theta)$. Regression coefficients k_i given in Fig.6 are obtained empirically.

B. Modeling the depolarization effect

The geometric interpretation of matrix $\mathbf{R}$ is an ellipse inclined by grain angle θ . This angle can be found by relating the transmission matrices in Eq(1) and Eq(2), using a rotation operation described by a 2 x 2 rotation matrix $\mathbf{M}$:

$$\mathbf{M} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \quad (3)$$

Then, relation (2) can be written as:

$$\begin{bmatrix} E_{T1} \\ E_{T2} \end{bmatrix} = \mathbf{M}^T \begin{bmatrix} R_H & 0 \\ 0 & R_V \end{bmatrix} \mathbf{M} \begin{bmatrix} E_{I1} \\ E_{I2} \end{bmatrix} \quad (4)$$

Combining (3) and (4), the transformation matrix is:

$$\begin{bmatrix} E_{T1} \\ E_{T2} \end{bmatrix} = \begin{bmatrix} \frac{R_H + R_V}{2} + \frac{R_H - R_V}{2} \cos 2\theta & \frac{R_H - R_V}{2} \sin 2\theta \\ \frac{R_H - R_V}{2} \sin 2\theta & \frac{R_H + R_V}{2} - \frac{R_H - R_V}{2} \cos 2\theta \end{bmatrix} \begin{bmatrix} E_{I1} \\ E_{I2} \end{bmatrix}$$

Thus, by measuring all four transmission coefficients, the grain angle θ can be calculated as:

$$\theta = \frac{1}{2} \text{atan} \left(\frac{R_{VH} + R_{HV}}{R_{VV} - R_{HH}} \right) \quad (5)$$

This agrees with findings published in [7-9]. The experimental confirmation, obtained measuring Sample 1 for seven angle positions is given in Table 1.

Table 1 Actual and measured grain angles for Sample 1

Actual θ	1	15	30	45	60	75	90
Measured θ	2.8	27.3	36.6	42	47.4	55.5	83.9

The presented theory gives an idealized presentation of the problem. The zero off-diagonal elements in the transmission matrix are obtained only when antennas have an ideal linear polarization. In reality, this is not the case and cross polarization has a small but finite value. The cross polar attenuation for measurement of a sample in a principal direction is approximately equal to the free space cross polar value.

Fig. 7 Cross polar transmission magnitude for three sample profiles

C. Direction of observation experiment

The second experiment considers depolarization measurements for the wave passing through a sample with a grain inclination in 3D space. Measurements were performed using a set of twenty two *Pinus Radiata* samples of size 5 x 10 x 40cm. Measurements are performed from two orthogonal propagation directions, which can be done either by using two pairs of antennas, as in Fig. 1, or by rotating the sample by 90°, which is done in this work. Four transmission coefficients magnitudes, marked as R_{VV} , R_{VH} , R_{HV} and R_{HH} , were measured in “front-to-back” direction, while the second set, R_{VV2} , R_{VL} , R_{LV} and R_{LL} , were obtained from measurements in “left-to-right” direction. In the conducted experiment, a sample is rotated around its vertical axis, so that for each of the four sets of measurements, a different surface of the sample is facing the receiving antenna. The cross polarization transmission magnitudes of these measurements are marked as ‘front’, ‘back’, ‘left’ and ‘right’ on the graph in Fig. 7.

D. Grain angle determination in 3D space

The presented findings show that the change in magnitude of cross polarization transmission coefficient closely follows the change in the arrangement of annual rings. This may be due to the fact that the grain usually lies within a plane determined by an annual ring. However, observing the annual ring pattern is not sufficient as grain can be inclined at any angle in that plane. Thus, in this section, determination of grain inclination in two orthogonal planes, described by angles θ and ϕ (Fig. 8), is considered.

Fig. 8 Grain angles in two orthogonal planes, given as θ and ϕ

Fig. 9 Visually and microwave determined grain angles for ten observed samples

Fig. 10 Correlation between visually and microwave determined grain angles

The reference grain angles are obtained by visual inspection of all four sides of the sample. This can be a difficult task, but here it was significantly simplified by visible traces of resin leakage along the grain, which occurred during the drying process. The grain direction was measured at several points on all four sides of the sample and the highest measured value was recorded. In Table 2, the grain angle on the wider side of the sample ('front-back direction') was marked as 'Visually measured θ ', while the angles obtained on the narrow sides ('left-right direction') are marked as 'Visually measured angle ϕ '. Using the model presented in Section III, in particular Eq. (5), grain angle values are calculated for the first ten samples in Fig. 7. Measured transmission coefficient magnitudes are given in Table 2, Fig. 9 and Fig. 10.

Although the actual grain angle values are not matched, the correlation between calculated and measured values is high, as can be noted in both figures. For this experiment, the free space measurement was not calibrated separately and this error is a contributing factor in observed discrepancies.

The results demonstrate that the presented technique has good potential as a practical tool for grain angle determination if additional calibration of the sensor is performed.

Table 2 Visually and microwave determined grain angles

Sample:		1	16	17	19	13	7	8	9	11	12
Microwave Transmission Coefficient Magnitude dB	VV	-24.3	-20.9	-23.8	-20.8	-20.4	-21.2	-19.9	-20.1	-21.1	-21.7
	HH	-17.8	-16.3	-17.7	-16.4	-16.0	-16.7	-16.1	-16.3	-16.9	-17.6
	VH	-45.3	-31.2	-42.8	-32.8	-50.2	-43.1	-44.0	-49.4	-40.8	-44.0
	VV2	-44.4	-34.5	-41.5	-36.5	-34.5	-35.1	-35.5	-35.3	-34.9	-35.9
	LL	-30.1	-28.4	-29.3	-29.3	-25.8	-27.2	-25.8	-26.3	-27.9	-27.5
Grain angle	VL	-66.6	-53.2	-66.4	-54.5	-45.9	-43.7	-46.4	-45.8	-41.5	-41.7
	Visually measured θ	5	9	5	8	3	3	3	0	3.0	3
	Microwave measured θ	5.0	20.6	6.2	18.8	2.8	6.6	6.4	3.5	9.2	7.2
	Visually measured ϕ	1	4	1	2	7	9	7	7	14.0	10
Grain angle	Microwave measured ϕ	4.6	6.4	1.1	5.5	8.6	13.3	7.8	9.0	18.6	16.0

IV. MICROWAVE SCATTERING MEASUREMENT

All experimental techniques reported to date, measure the transmission of a plane wave through a sample, with receiving and transmitting antennas in a co-linear arrangement. Departing from that approach, we investigate any additional information that may be obtained by performing measurements over two non-parallel planes around the sample. The Focused Beam system was used to detect scattering from the sample in two orthogonal directions. Again, the measurement setup in Fig. 1 was used, but now, besides the transmission coefficient S_{12} , measured using the transmitting antenna Tx1 and the receiving antenna Rx1, we define a scattering coefficient S_{13} , measured as the transmission from antenna Tx1 to the receiving antenna Rx2. In addition, taking into account the wood anisotropy, the sample was rotated around the axis so that each time a different side faces the transmitting antenna.

Comparing the measured scattering coefficients for VV, HH and VH polarizations, it was noticed that each of the samples has a slightly different magnitude for VV polarization, but less so for the other nominal polarization, HH; while the cross polar measurements, VH and HV, show very little variation for both difference between the samples and one sample observed from different directions. The correlation of the VV scattering coefficient with several structural properties of the wood was then investigated, namely with bulk density, density variation, presence of defects and cutting pattern (i.e. the annual ring arrangement).

Bulk density Microwave data are obtained by averaging the measured scattering coefficient magnitudes over the frequency range. That way, for each sample, a single value of scattering coefficient S_{13} was obtained. The scattering coefficient was related to the density of the volume illuminated by the beam, obtained from X-ray CT scans of the sample. The obtained results indicate that measured scattering coefficient does not depend on sample density, as the correlation is poor, with R^2 less than 0.19 for four observation directions.

Fig. 11 Scattering coefficient S13

Gradual density variation Here, the transmission S_{13} is considered to be a consequence of scattering from the boundaries within the sample. The maximum and minimum values of density in the sample are obtained from X-ray CT scans. The difference between these two values is used as a measure of density variation, which is then correlated with the measured scattering coefficient S_{13} . The correlation is very poor, with R^2 less than 0.076, for four observation directions, showing that small variations in density within the sample do not contribute to the sideways scatter.

Defect categories We investigate whether the presence of defects causes the transmission in the S_{13} direction. Based on inspection of CT scans and visual detection of defects, all samples are categorized into four groups: clear samples (category A), samples with variation in annual ring orientation (B), samples with small defects such as needle fleck (C) and knots (D). Measured microwave values are averaged and sorted in ascending order. Clusters of the same code letter are expected for the case when this categorizing has an influence. Unfortunately, poor correlation was obtained, as indicated in Fig. 11, showing measured S_{13} values observed from front side in VV polarization. It is clear that defects do not determine the level of scattering in the sideways direction.

Annual ring orientation In the final experiment, samples are grouped based on the pattern made by the annual rings (AR) in the sample cross section. Table 3 shows five categories, starting from category V with vertical annual rings and going gradually towards category H with a horizontal annual ring pattern. Sample 21 is an odd one out since it does not fit in

any of the categories due to a change in the ring orientation along the sample. For each category, a code letter is assigned, given in the second column of Table 3, followed by the list of samples belonging to the category. A typical appearance is shown on the photo of sample cross sections, given in the last column of Table 3. The statistics of each measurement are then calculated and obtained mean value of scatter coefficient S_{13} are given Table 4 and in a bar graph (Fig. 11), using the adopted code names for sample groups.

Table 3 Sample categories

AR direction	Code	Samples	Appearance
Vertical	V	4,9,13
Vertical to slope	VS	8, 12, 11, 7
Slope 1	S1	6, 14, 15, 22, 20
Slope 2	S2	5, 10, 18
Horizontal	H	1,2, 3, 16, 17, 19

It can be noted that samples in group ‘Slope 1’ have much higher level of scatter in the observed direction. These are the samples 6, 14, 15, 20 and 22, as shown in Table 3. It can be speculated that samples in this category have an arrangement of earlywood / latewood layers which allows a guiding of a wave incident to the front side of the sample towards the S_{13} position. The structure of wood [1] shows that two layers, earlywood and latewood, can be distinguished by a percentage of dry matter in their structure. This indicates that earlywood has higher effective permittivity than latewood, which is experimentally confirmed by Schinker et al. [12] who measured the permittivity of earlywood and latewood layers using a dielectric probe.

Table 4 Mean S_{13} values for samples grouped in categories

Sample	4	9	13	7	8	11	12	
Code	V	V	V	VS	VS	VS	VS	
Mean	-49.4	-46.1	-44.9	-48.5	-46.8	-45.7	-48.1	
Sample	6	14	15	20	22	5	10	18
Code	S1	S1	S1	S1	S1	S2	S2	S2
Mean	-40.3	-32.8	-32.8	-38.2	-33.3	-44.8	-48.3	-46.9
Sample	1	2	3	16	17	19	21	
Code	H	H	H	H	H	H	H	
Mean	-43	-44.5	-41.1	-45.2	-42.1	-44.4	-42.0	

It is possible that such a periodically layered structure supports wave transmission and is responsible for the higher level of scattering coefficient in S_{13} direction. Further research on this topic is recommended to explain the findings reported here.

V. CONCLUSION

The motivation for the anisotropy study comes from indications that wood strength can be related to the wood grain direction. In literature published to date, the grain inclination is considered only in a plane which is parallel to the wave

front of an incident wave and it has been described by a single inclination angle θ . Such an approach significantly limits practical application of the sensing technique. In this paper, the problem of three-dimensional anisotropy is considered and a demonstrated technique shows promising results. Although the actual grain angle values do not closely match the calculated values, the correlation between two data sets is high, with $R^2 = 0.74$ for θ and $R^2 = 0.91$ for ϕ . This indicates that such a sensor has the capability to detect the variation in the grain angle and accurate values could be obtained by means of additional calibration.

In the second part of the paper a relation between annual ring orientation and higher level of scattering in sideways direction was demonstrated. Although the findings of this experiment do not lead to a design of a practical sensor, they are interesting as an illustration of the complexity of the structure of wood and the means by which the wood material affects a propagating wave. It also shows that the plane wave propagation model is very simplified and as such cannot provide accurate prediction of the wave behavior in such complex media.

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