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ORIGINAL ARTICLE

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Predicting moisture content and density distribution of Scots pine by microwave scanning of sawn timber II: evaluation of models generated on a pixel level

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Abstract The purpose of this study was to use images from a microwave sensor on a pixel level for simultaneous prediction of moisture content and density of wood. The microwave sensor functions as a line-scan camera with a pixel size of 8 mm. Boards of Scots pine (*Pinus sylvestris*), 25 and 50 mm thick, were scanned at three different moisture contents. Dry density and moisture content for each pixel were calculated from measurements with a computed tomography scanner. It was possible to create models for prediction of density on a pixel level. Models for prediction of moisture content had to be based on average values over homogeneous regions. Accuracy will be improved if it is possible to make a classification of knots, heartwood, sapwood, etc., and calibrate different models for different types of wood. The limitations of the sensor used are high noise in amplitude measurements and the restriction to one period for phase measurements.

Key words Microwave scanning · Wood · Density · Moisture content

Introduction

There is an increasing need in the wood industry for precision on-line measurement of moisture content (MC) and density. This information could be used for individual drying of the boards or for quality and stress grading. A microwave signal will be affected by several properties such as density, MC, temperature, and grain angle when it is transmitted through wood. These properties have influence on attenuation, phase shift, and polarization of the signal. Moisture measurements can be improved by combining measurements of both attenuation and phase shift[1] or measurements of phase shift at two frequencies.[2] Another possibility is to use measurements of different microwave parameters for concurrent prediction of several wood properties from one noninvasive measurement. This has been done, for example, by Bolomey et al.[3] and Choffel et al.[4]

The present study is based on work by Johansson et al.[5] in which multivariate models to predict MC and density for boards of Scots pine (*Pinus sylvestris*) were calibrated using average values over the boards. The purpose of the present work was to evaluate and develop this method with models generated on a pixel level wherein each pixel was treated as one observation.

Theory

Consider a plane electromagnetic wave propagating through wood in the z-direction. If losses due to conductance and reflections are ignored, the attenuation and wavelength are governed by the factor $e^{-\gamma z}$, with the complex propagation constant,[6]

$$\gamma = j\omega\sqrt{\varepsilon^{*}\varepsilon_0\mu'\mu_0} = \alpha + j\beta, \tag{1}$$

where ω is the angular frequency of the wave, $\varepsilon^{*} = \varepsilon' - j\varepsilon''$ is the complex dielectric constant, $\mu' \approx 1$ is the relative permeability of wood, and $\varepsilon_0 = 1/(\mu_0 c_0^2)$ is the permittivity of free space where c_0 is the speed of light in free space.

The real part of γ can be defined as an attenuation constant,

$$\alpha = \frac{\omega}{c_0}\left[\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)\right]^{\frac{1}{2}} \tag{2}$$

and the imaginary part of γ as a phase constant,

$$\beta = \frac{\omega}{c_0}\left[\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta} + 1\right)\right]^{\frac{1}{2}} \tag{3}$$

where $\tan\delta = \varepsilon'/\varepsilon''$ is defined as the loss tangent.

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For low moisture content ($\tan\delta << 1$) it has been shown by King[7] that these expressions for α and β can be simplified from binomial expansion of Eq. 1:

$$\gamma = j\beta_0\sqrt{\varepsilon'(1-j\tan\delta)} = j\beta_0\sqrt{\varepsilon'}\left[1-j\frac{\tan\delta}{2}+\frac{\tan^2\delta}{8}+\ldots\right] \quad (4)$$

where $\beta_0 = 2\pi/\lambda_0$ is the phase constant of air and λ_0 is the wavelength of the electromagnetic wave in air. Thus Eqs. 3 and 4 can be approximated as

$$\alpha = \frac{1}{2}\beta_0\sqrt{\varepsilon'}\tan\delta \quad (5)$$

and

$$\beta = \beta_0\sqrt{\varepsilon'}\left(1+\frac{1}{8}\tan^2\delta\right). \quad (6)$$

King[7] suggested that α should be used for prediction of MC and β should be used for prediction of density. However, tabulated values from Torgovnikov[8] plotted in Figs. 1 and 2 show that both ε' and $\tan\delta$ are correlated to wood density and moisture content. The complex relation between microwaves and wood properties indicates that multivariate methods are beneficial for simultaneous prediction of moisture content and dry density.

Material and methods

The study was based on 96 boards of Scots pine (*Pinus sylvestris*), 48 with a cross section 150 × 50 mm and 48 with a cross section 150 × 25 mm. The 48 boards with a thickness of 50 mm consisted mainly of heartwood, while the amount of heartwood in the boards with a thickness of 25 mm varied from 0% to 100%. Examples of these variations are shown in Fig. 3.

The boards originated from two different parts of Sweden. Half of the boards of each dimension were sawn at a mill in Skellefteå (Wallmarks) situated in the northern part of Sweden. The other 48 boards were sawn at a mill in Ljungby (Vida), situated in the southern part of Sweden. Before scanning, each board was cut to a length of 1600 mm, and a 25-mm hole was drilled as a reference point.

The moisture content (MC) in some of the freshly sawn boards exceeded the dynamic measurement range of the microwave scanner. There was also a large variation in the moisture distribution at higher moisture contents. Therefore, this study is limited to measurements below the fiber saturation point (FSP), which corresponds to a MC of approximately 30%. The boards were dried from green condition to 7% MC. At three different moisture levels, the boards were removed from the kiln and scanned with microwaves and X-rays. Figure 4 shows an X-ray image of the scanned region from one board. The light regions in the image represent areas with high density.

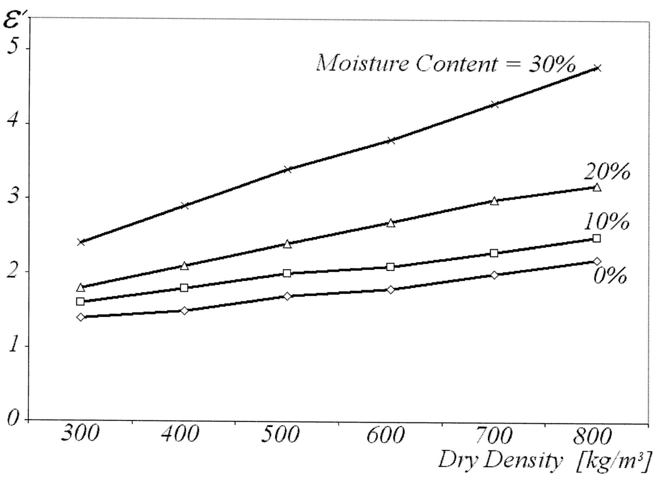

Fig. 1. Real part of the dielectric constant (ε') perpendicular to the grain as a function of dry density and moisture content at 10 GHz (data from Torgovnikov)[8]

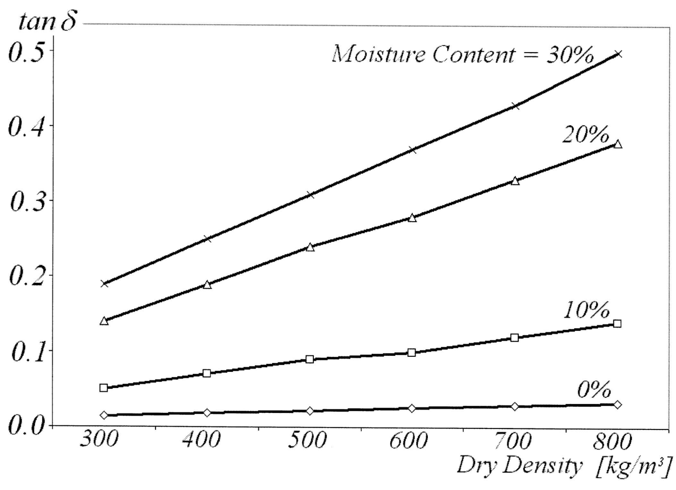

Fig. 2. Loss tangent ($\tan\delta$) perpendicular to the grain as a function of dry density and moisture content at 10 GHz (data from Torgovnikov)[8]

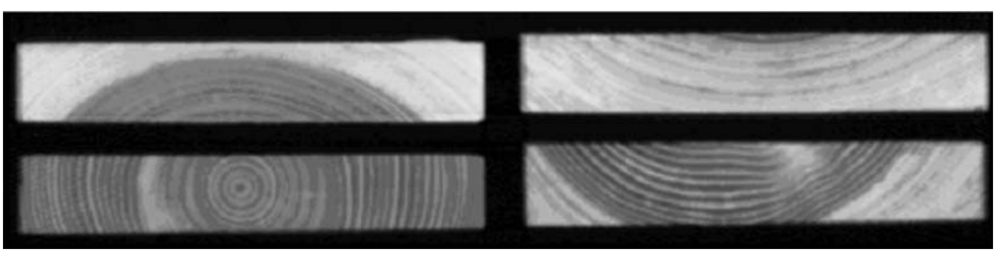

Fig. 3. Cross sections from computed tomography (CT) scanning of four different boards in green condition. The high moisture content (MC) gives high density in the sapwood compared with heartwood

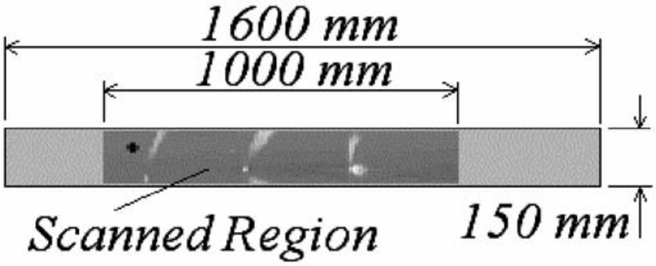

Fig. 4. Image of one board from the CT scanner after transformation to two dimensions. A length of 1 m of each board was scanned

Drying

The freshly sawn boards were dried in a small kiln. In order to determine the average moisture content for the boards, they were weighed after each drying step. The target moisture content at each drying step was set to 20%, 12%, and 7%. After the last scanning, the dry weight of each board was estimated from five samples taken at even intervals along the board. The moisture content was assumed to be evenly distributed in the boards after the last drying to 7% MC. From that assumption the dry density in each pixel was calculated using the density measured in a computed tomography (CT) scanner. The dry density was used to calculate MC in each pixel from the measured density in the remaining observations. No corrections were made for shrinkage, because the maximum shrinkage was less than one pixel.

X-ray scanner

A CT scanner (Siemens Somatom ART) was used to scan the boards every 8 mm with a 5-mm-wide X-ray beam. The scanner measures density in three dimensions with high accuracy.[9] The images from the CT scanner were transformed to two dimensions by taking mean values of density variations through the boards.

Microwave scanner

Using a transverse feeding direction, the boards were scanned with a microwave sensor (Satimo 9.375 GHz) in combination with a computer and a conveyer described by Johansson.[10] The system produces images with a pixel size of 8 × 8 mm. The sensor is based on electromagnetic transmission through the wood and a modulated scattering technique, which is described by Bolomey and Gardiol.[11] The sensor measures the real and imaginary part of the electromagnetic field in two orthogonal polarization angles. From these variables, the linear and decibel amplitude and the phase shift were calculated. All of these five variables were measured and calculated in four different polarization angles: horizontal, vertical, plus 45 degrees and minus 45 degrees. This gives a total of 20 variables describing attenuation, phase shift, and polarization of the transmitted field.

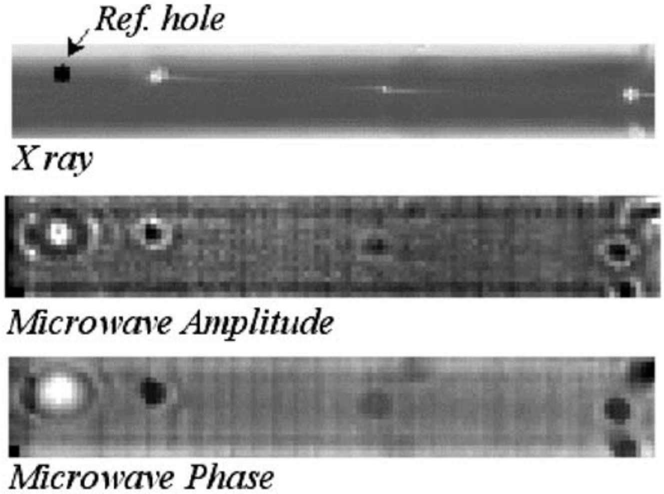

Fig. 5. Example of images from X-ray scanning and microwave measurements on phase shift and amplitude of one board. Several knots are visible in the images

Figure 5 shows an example of attenuation and phase shift measured in one direction with the microwave sensor compared with density measured with X-rays.

Multivariate models

Models for prediction of dry density and moisture content were calibrated using partial least squares (PLS) regression as described by Martens and Næs[12] using the Simca P+ 10.0 software from Umetrics. Average dry density and MC of the wood were calculated from CT images for each pixel in the microwave image and were used as response variables. The variables from the microwave scanner were used as predictors. Each variable was centered and scaled to unit variance. Using the PLS algorithm means that uncorrelated principal components (PC) are formed as linear combinations of the correlated variables from the microwave scanner. The numbers of PCs were optimized by the software to two or three depending on the response variable. The available amount of memory restricted the number of observations to 200 randomly selected pixels from each board. No distinction was made as to whether the points came from heartwood, sapwood, or knots. About 80% of the observations were used as a training set for calibrating the models. The remaining, randomly selected observations were used as a test set for verification of the models. This gave about 23 000 observations in the training set and 5700 observations in the test set for each thickness.

Results

Moisture content

Models based on values from randomly selected pixels turned out to be weak and noisy with a correlation coeffi-

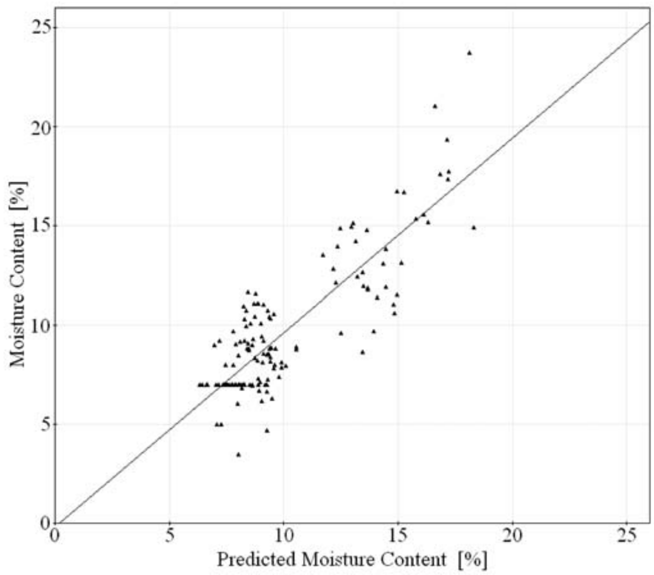

Fig. 6. Measured versus predicted moisture content for 25-mm boards based on mean values over five regions from each board

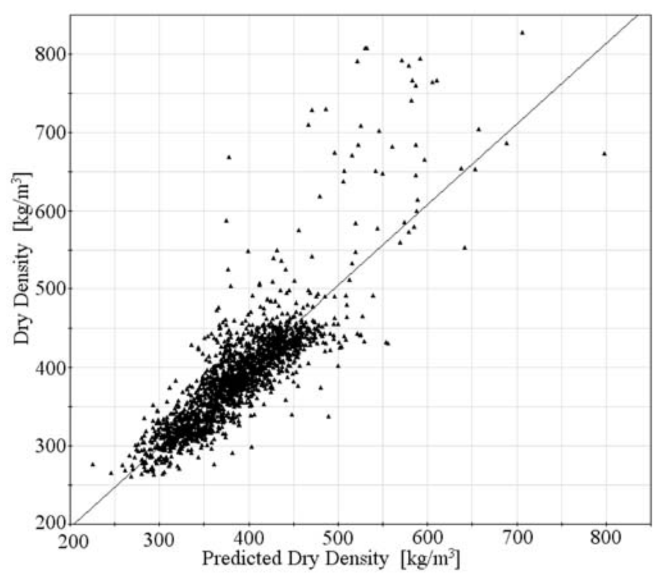

Fig. 8. Measured versus predicted dry density for 25-mm boards based on values from randomly selected pictures

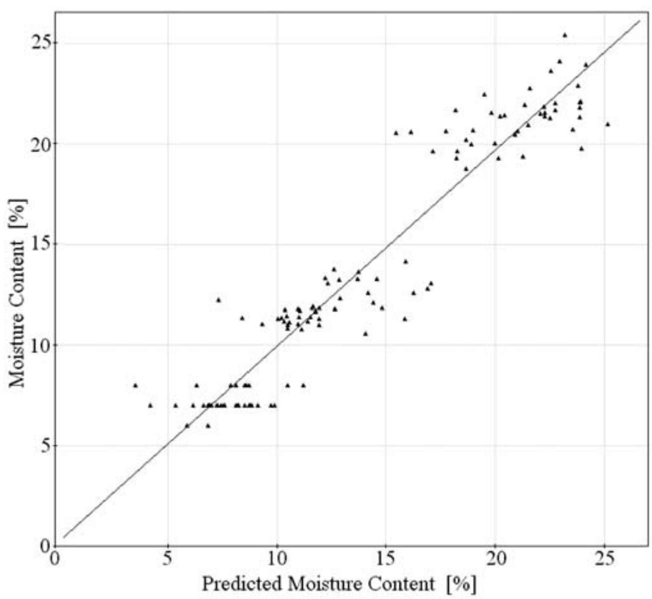

Fig. 7. Measured versus predicted moisture content for 50-mm boards based on mean values over five regions from each board

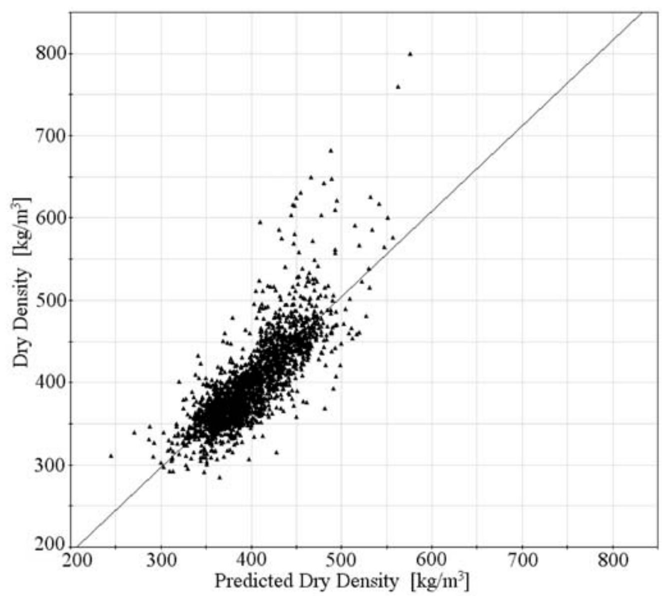

Fig. 9. Measured versus predicted dry density for 50-mm boards based on values from randomly selected pixels

cient R^2 of approximately 0.20. To avoid this problem, the models for MC shown in Figs. 6 and 7 are based on average values over five homogeneous regions from each board with sizes varying from 0.0025 to 0.015 m^2. This reduces the number of observations for each thickness to about 550 in the training set and 130 in the test set used for the verification that is shown in the figures. The model for prediction of MC for 25-mm boards has a correlation coefficient $R^2 = 0.72$ and estimated root mean square error RMSEP = 1.8% MC. The model for 50-mm boards has $R^2 = 0.90$ and RMSEP = 2.0% MC.

Density

The models for prediction of dry density shown in Figs. 8 and 9 are based on values from 200 pixels in each board. The model for prediction of dry density for 25-mm boards has $R^2 = 0.71$ and RMSEP = 38 kg/m^3. The model for 50-mm boards has $R^2 = 0.64$ and RMSEP = 32 kg/m^3. The randomly selected pixels also contain some high-density values from knots that the model is not able to describe properly.

Discussion

The 50-mm boards consisted mainly of heartwood, with the exception of three boards that showed up as outliers in the model and were excluded from the dataset. One board was also excluded because of rot. It would have been desirable to classify the amount of sapwood in the 25-mm boards in order to find correlations. This was not done, but five boards consisting mainly of heartwood were identified as outliers in the dataset and were excluded. There was no significant difference between the two groups of boards originating from different parts of Sweden.

The variables describing phase shift are periodic and the variation was more than one period between measurements at different MC. This made it impossible to compare these measurements without calibration to a known reference. Therefore, models for MC were mainly based on variables describing amplitude. It can be deduced from Eq. 5 in combination with Fig. 2 that MC should have a strong influence on amplitude. However, reflection and scattering at boundaries where the changes in dielectric properties are large caused large local variations in amplitude. This explains why models for MC could not be based on pixel values. Variations in phase shift caused by differences in dry density were less than one period. Therefore, the variables describing phase shift could be used as strong predictors for dry density.

Conclusions

A good model for prediction of density can be calibrated from pixel values. It is possible to calibrate a satisfactory model for moisture content from average values over homogenous regions, but not from pixel values. Edges, knots, and other regions where properties change will cause errors in the models. These errors can be reduced by taking the average over a large area. If algorithms that classify the regions could be created, it would be possible to use different prediction models for different regions. An improved microwave sensor for wood scanning should measure phase shift over several periods, for example, by using two frequencies. It should also produce less noise in the amplitude measurements.

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