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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

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Abstract This study was carried out to investigate the possibility of calibrating a prediction model for the moisture content and density distribution of Scots pine (*Pinus sylvestris*) using microwave sensors. The material was initially of green moisture content and was thereafter dried in several steps to zero moisture content. At each step, all the pieces were weighed, scanned with a microwave sensor (Satimo 9,4 GHz), and computed tomography (CT)-scanned with a medical CT scanner (Siemens Somatom AR.T.). The output variables from the microwave sensor were used as predictors, and CT images that correlated with known moisture content were used as response variables. Multivariate models to predict average moisture content and density were calibrated using the partial least squares (PLS) regression. The models for average moisture content and density were applied at the pixel level, and the distribution was visualized. The results show that it is possible to predict both moisture content distribution and density distribution with high accuracy using microwave sensors.

Key words Microwave scanning · Density · Moisture content · Multivariate calibration · PLS regression

Introduction

One of the most important tasks for the wood industry to maintain its position in competition with substitutes such as steel and polymers is to transform wood into an engineering material. To achieve that, one must find inexpensive, fast, nondestructive methods for measuring the properties of each board. Efficient processing can be reached only through knowledge of the properties of the individual piece in which to set the processing parameters (e.g., a fast-drying process or a cross-cutting optimization line). To be able to predict both the density and moisture content distribution of sawn timber would be of great interest to most sawmills. The ability to sort boards by density and moisture content before drying would mean that each board could be dried the right way and to the right moisture content with reduced drying defects and drying time. Moisture content prediction after drying would be good feedback to the drying process and an excellent tool for drying research. Density prediction could also be used as a tool for either visual or automatic strength grading, as density is one of the most important variables when predicting the strength and stiffness of wood.[1]

Interactions between the complex microstructure and macrostructure of wood and the complex microwave field have been the object of several studies. For example, density calibrations have been done by Choffel et al.[2] and Bolomey et al.,[3] moisture content calibrations have been done by Bolomey et al.,[3] and slope of grain predictions and strength predictions have been assessed by Choffel et al.[2] and Leicester.[4]

One of the major problems of calibration is the richness in the microwave signals after interaction with the inhomogeneous wood material. Multivariate calibration using partial least squares (PLS) regression[5] gives information about more than one physical mechanism based on the dielectric property of the wood, which depends on wood density and moisture content. It also depends on temperature, field frequency, and the field orientation in relation to the grain angle of the wood.[6]

Methods and materials

This study was based on seven pieces of Scots pine with cross sections of 125 × 25 mm. The pieces were selected to achieve varied dry densities among the pieces. All material was initially of green moisture content; thereafter, it was dried in four steps to zero moisture content. At each step all

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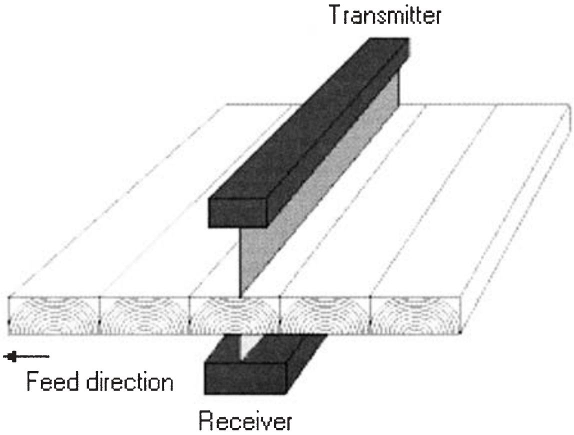

Fig. 1. Microwave scanning principles

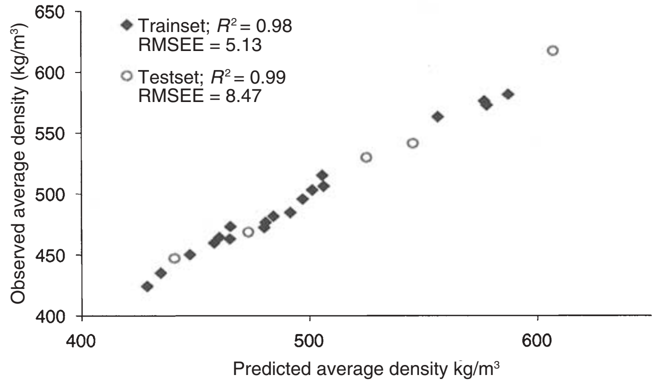

Fig. 2. Observed/predicted average density below the fiber saturation point. *RMSEE*, root mean square error of estimation

of the pieces were weighed, scanned with a microwave sensor (Satimo 9.375 GHz), and computed tomography (CT)-scanned with a medical CT scanner (Siemens Somatom AR.T.). For the first drying step, above the fiber saturation point, microwave power was used to avoid moisture gradients in the boards. The subsequent drying steps were conducted using a conventional air-drying technique in a climate chamber.

Using the transverse feeding direction, each board was scanned every 8 mm with a microwave sensor at 9.375 GHz (Fig. 1). The sensor described by Bolomey[7] has a transmitting antenna and a receiving antenna, and it consists of 128 dual polarized elements with 8 mm distance between each element. The measurement principle is electromagnetic transmission by a quasi plane wave through the wood. The modulated scattering technique was used for signal processing. The output variables were the imaginary and real parts of the electromagnetic field, and the amplitude, linear and decibel, and the phase shift were calculated from these variables. All five variables were measured and calculated using four polarization angles: horizontal, vertical, +45 degrees, and −45 degrees. Finally, reference measurements were done using pieces with a similar moisture content, giving a total of 40 variables or predictors.

A medical CT scanner (Siemens Somatom AR.T.) was used to scan the boards every 8 mm with a 5 mm wide X-ray beam. The CT images (8-bit, 512 × 512 pixels) were then used to measure the density distribution of each board.

The moisture content was calculated using the density measurements with the boards dried to zero moisture content as references. Multivariate models were then calibrated using PLS regression and SIMCA 7.01 software (Umetri AB), with the 40 variables from the microwave sensor as predictors and two variables (density and moisture content) from the CT scanner as response variables. About 80% of the observations were used as a training set for calibrating the models, and the remaining observations were used as a test set for verifying the models. The observations for the test set were randomly chosen within and between classes (i.e., moisture content and density classes).

All models, except moisture content below the fiber saturation point, were calibrated using orthogonal signal correction (OSC), which is a PLS-based filtering technique that removes variations that are mathematically independent of Y from the X data.[8] The models calibrated for average density and moisture content were applied to each pixel below the fiber saturation point, and the predicted distribution was visualized.

The case above fiber saturation point is special and is studied only on an average basis. The reason for this is that sapwood and heartwood have different moisture content properties above the fiber saturation point, which results in difficulties with wood drying and requires a special study on a distribution basis.

Results and discussion

Two models were calibrated for both density and moisture content: one below and the other above the fiber saturation point. This was achieved by calibrating a model for classifying the boards. The model was calibrated for classifying boards above and below the fiber saturation point (i.e., 30% moisture content) with a correlation of 100%. The density model for 25 mm, below the fiber saturation point (Fig. 2), has good accuracy, with $R^2 = 0.98$ and a root mean square error of estimation (RMSEE) of 5.13 kg/m^3 for the training set and $R^2 = 0.99$, RMSEE = 8.47 kg/m^3 for the test (Fig. 2). The average density model below the fiber saturation point applied to each pixel and visualized by a topogram (Fig. 3) compared to the density topogram by X-rays (Fig. 4) shows good correlation within and between boards. The largest errors occur at knots and at board edges.

The knot error predicted by microwaves is shown to be flatter and wider than knots visualized by X-rays (Fig. 5). The errors at board edges are shown by decreased density near the edges. Errors are reduced if the boards are scanned tightly together with as little distance as possible between the boards.

The moisture content model for 25 mm, below the fiber saturation point (Fig. 6), has an accuracy of $R^2 = 0.99$ and

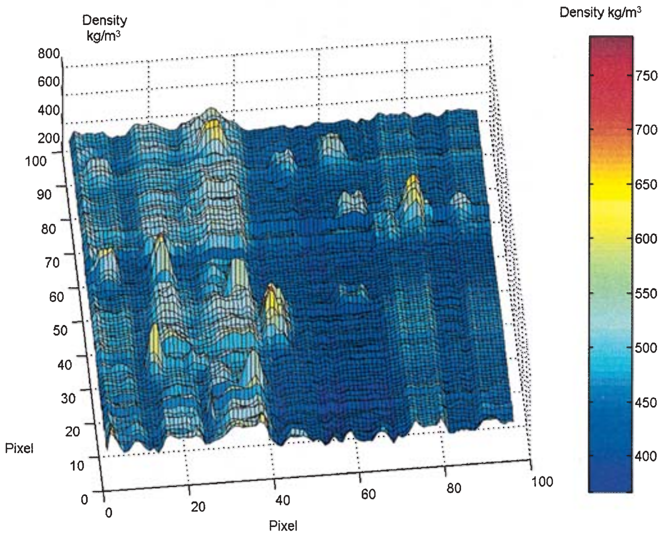

Fig. 3. Density distribution predicted by microwaves below the fiber saturation point. Seven boards with different densities, from left to right

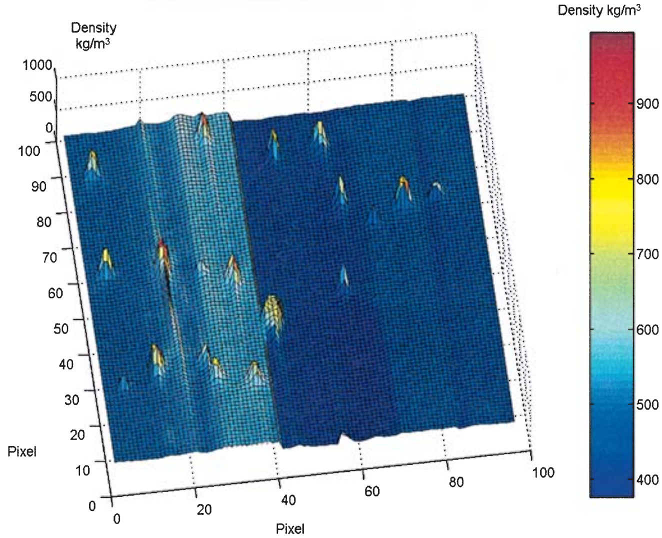

Fig. 4. Density distribution by X-rays below the fiber saturation point. Seven boards with different densities, from left to right (same boards as in Fig. 3)

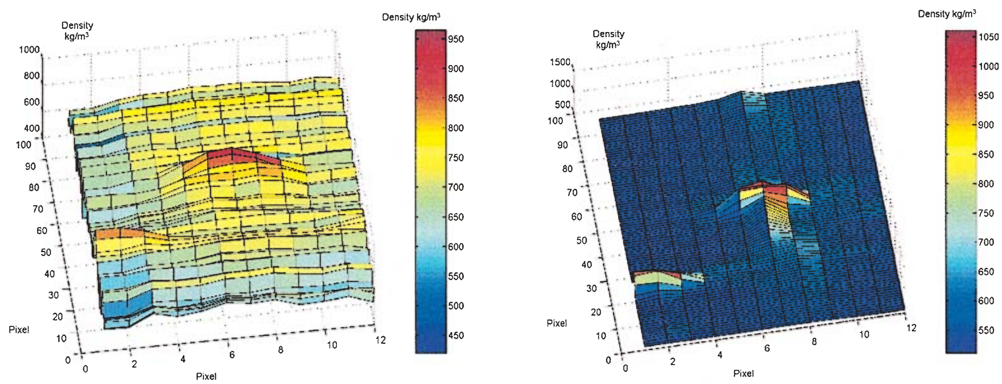

Fig. 5. Density distribution of one board. **Left** Microwaves. **Right** X-rays

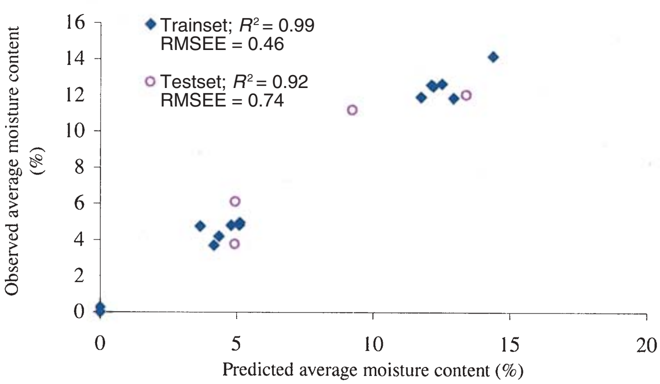

Fig. 6. Observed/predicted average moisture content below the fiber saturation point

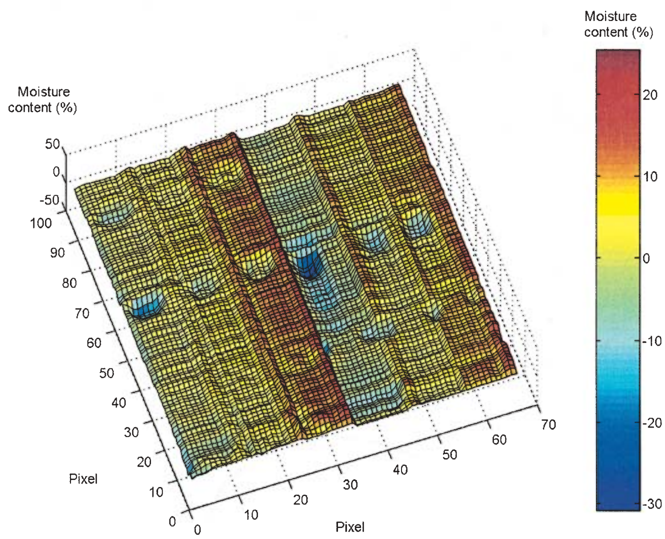

Fig. 7. Moisture content distribution predicted by microwaves. From left to right: the first three boards are the same boards with different moisture contents. The last three boards are different boards with three moisture contents

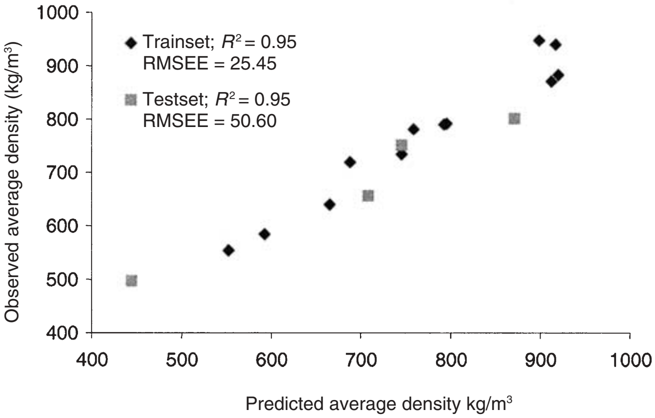

Fig. 8. Observed/predicted average density above the fiber saturation point

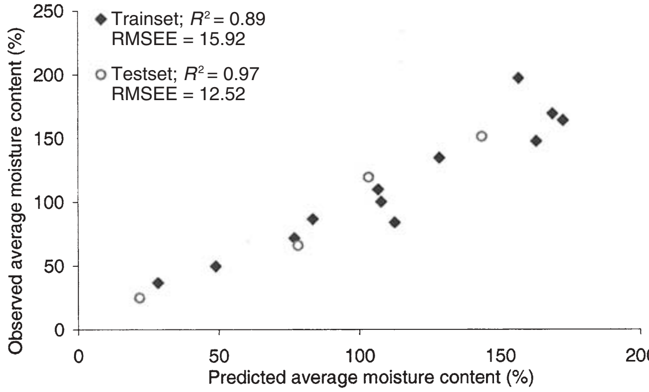

Fig. 9. Observed/predicted average moisture content above the fiber saturation point

RMSEE = 0.46% moisture content for the training set and R^2 = 0.92, RMSEE = 0.74% moisture content for the test set.

The model calibrated for the average moisture content below the fiber saturation point applied to each pixel is seen in Fig. 7, where two boards with three levels of moisture content are shown. As seen in the topograms, the largest errors occur at the edges between the boards, whereas the distribution of moisture content in and between the boards shows good accuracy based on the knowledge that average levels are accurate.

Much effort has been exerted to compare the pixel-by-pixel distribution between boards with different moisture contents scanned with microwaves and X-rays. This has proven to be almost impossible to do with reasonable accuracy and effort because when comparisons are made between a board at different moisture contents the board has been deformed in several ways. It has been swollen or has shrunk differently in all three directions, twisted around its axes, and bent in two directions. Errors also occur because of position and measuring inaccuracy, which has made it impossible to compare pixel-by-pixel and to create a moisture content topogram of X-rays to compare with microwaves in Fig. 7.

The average density above the fiber saturation point (Fig. 8) has an accuracy of R^2 = 0.95 and RMSEE = 25.45 kg/m³ for the training set and R^2 = 0.95 and RMSEE = 50.60 kg/m³ for the test set. The average moisture content above the fiber saturation point (Fig. 9) has an accuracy of R^2 = 0.89 and RMSEE = 15.92% moisture content for the training set and R^2 = 0.97 and RMSEE = 12.52% moisture content for the test set.

Conclusions

The promising results from this study show that microwave techniques can be used to predict moisture content and density distribution of Scots pine. It is possible to predict both moisture content and density distribution using different prediction models. It is also possible to classify boards according to whether their moisture contents are above or below the fiber saturation point.

The largest errors occur at board edges and around knots. Errors at board edges are reduced if the boards are scanned tightly together with as little distance as possible between the boards. One way to deal with this problem is to use the transverse feed direction with feed pressure. Another advantage of the transverse feed direction is that an error or disturbance at one diode, or "pixel," at the sensor creates far less damage to the data output using transverse feed instead of lengthwise feed and can be detected and filtered more easily. The fact that most sawmills use transverse feed in their sorting lines makes it easier to integrate the scanner system into the sawmill layout.

Errors around knots are of less importance if one wants to measure the distribution of density or moisture content, as the knot topograms only are a bit wider and flatter. If one wants to measure the knot parameters more exactly, digital filters must be developed. It is not possible to measure small knots (<8 mm) properly.

The high accuracy of the density prediction indicates that it may be possible to predict the strength and stiffness of wood using microwaves based on density predictions, as density is one of the most important variables when predicting the strength and stiffness of wood.[1] Other variables that influence strength are knot size, knot type, knot position, and fiber angle. These variables are detectable by microwave sensors.[2,9] Consequently, our results are interesting for future work, especially the possibility that one can, by multivariate calibration, predict the strength and stiffness of wood using density prediction combined with other strength-influencing variables.

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