J Wood Sci (2006) 52:406–410
DOI 10.1007/s10086-005-0794-8

ORIGINAL ARTICLE

Lars Hansson · Nils Lundgren · Anna-Lena Antti
Olle Hagman

Finite element modeling (FEM) simulation of interactions between wood and microwaves

Received: April 4, 2005 / Accepted: November 11, 2005 / Published online: April 25, 2006

Abstract The aim of this study was to use finite element modeling (FEM) as a tool to analyze microwave scattering in wood and to verify the model by measurements with a microwave scanner. A medical computed tomography scanner was used to measure distribution of density and moisture content in a piece of Scots pine (*Pinus sylvestris*). Dielectric properties were calculated from measured values for cross sections from the piece and used in the model. Images describing the distribution of the electric field and phase shift were obtained from the FEM simulation. The model was verified by measurements with a scanner based on a microwave sensor. The results show that simulated values correspond well to measured values. Furthermore, discontinuities in the material caused scattering in both the measured and the simulated values. The greater the discontinuity in the material, the greater was the need for computational power in the simulation.

Key words Microwave scanning · Wood · Dielectric properties · Modulated scattering technique · Finite element modeling

Introduction

Microwave scanning is a fast and nondestructive method of measuring internal properties, such as density and moisture content (MC) of wood. This method has previously been studied, for example, by Johansson et al.[1] The aim of the present study was to use finite element modeling (FEM) as a tool to analyze microwave scattering in wood and to verify the model by measurements with a microwave scanner. Values of phase shift and attenuation from the measurements were compared with the FEM model.

By transforming the Maxwell equations into second-order partial differential equations (PDEs) it is possible to solve electromagnetic wave propagation problems. Because wood is an inhomogeneous and anisotropic dielectric material, the wave scatters in different directions as it propagates. Moisture and heat flow during microwave drying of wood have been modeled by Antti,[2] Perre and Turner,[3] and Zhao and Turner.[4] No previous models have been made of electromagnetic wave propagation inside wood because of difficulties in ascertaining the internal structure and because of the need of computational power. In the present analysis, the internal structure of density and moisture content in wood was determined by computed tomography (CT) scanning, as described by Lindgren.[5] From these density and moisture content values, the distribution of dielectric properties was determined. The finite element modeling electromagnetic module in FEMLAB[6] version 3.1 software was used to solve PDEs that describe the wave propagation.

L. Hansson · A.-L. Antti
Division of Wood Physics, Luleå University of Technology, Skellefteå Campus, Skellefteå SE-931 87, Sweden

N. Lundgren (✉) · O. Hagman
Division of Wood Technology, Luleå University of Technology, Skellefteå Campus, Skellefteå SE-931 87, Sweden
Tel. +46-910-58-5707; Fax +46-910-58-5399
e-mail: nils.lundgren@ltu.se

Theory

The dielectric properties of wood depend on moisture content, density, frequency, grain angle, and temperature. The real and imaginary part of the dielectric permittivity, ε' and ε'', perpendicular to the grain versus moisture content and density are shown in Figs. 1 and 2. The free water in the cell cavities, when above the fiber saturation point (FSP), seems to affect permittivity values somewhat differently from water that is bound in the cell walls. Parallel to the grain, the values are 1.1–2 times higher.[7]

Simulation models were constructed with the finite element method as described by, among others, Jin[8] using FEMLAB[6] 3.1. The models describe how a transverse electric (TE) wave propagates through a piece of wood surrounded by air. The variations in the material require a three-dimensional model to obtain a correct solution. How-

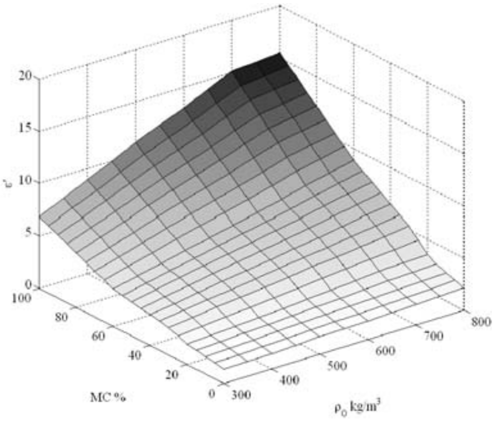

Fig. 1. The relative permittivity ε' at 10 GHz and room temperature, perpendicular to the grain versus moisture content and density[7]

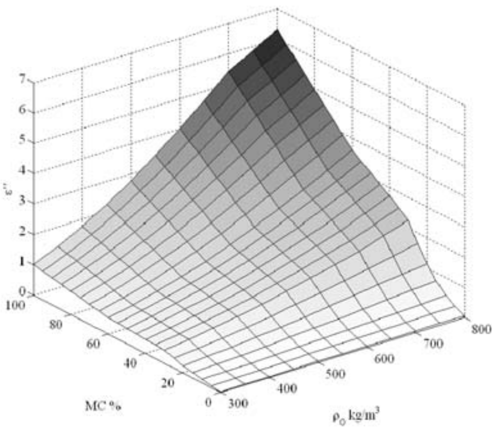

Fig. 2. The relative loss factor ε'' at 10 GHz and room temperature, perpendicular to the grain versus moisture content and density[7]

ever, insufficient computational power made it necessary to restrict the simulation to a two-dimensional model. Variations of dielectric properties in the z direction were neglected, which may increase the errors in the final solution. In the model domain, the z component of the $\boldsymbol{E}$ field is solved by the following equation:

$$\nabla \times \left(\frac{1}{\mu_{\mathrm{r}}} \nabla \times \boldsymbol{E}_z \right) - \left(\varepsilon^* - j \cdot \frac{\sigma}{\omega} \cdot \varepsilon_0 \right) \cdot k_0^2 \cdot \boldsymbol{E}_z = 0, \tag{1}$$

where μ_{r} is the relative permeability, which is equal to the permeability μ_0 of the free space in the total model domain, because wood is not a magnetic material. Furthermore, ω is the angular frequency, σ is the conductivity, and k_0 is the wave number in free space. In this case σ is close to zero. ε^* is the dielectric permittivity defined as:

$$\varepsilon^* = \left(\varepsilon' - j \cdot \varepsilon'' \right), \tag{2}$$

where ε' is the relative permittivity and ε'' is the relative loss factor. Tables from Torgovnikov[7] that describe ε^* at varying moisture content, density, and temperature are included in the model and values for ε' and ε'' are interpolated for each grid point and time step by the solver. The model uses a low-reflectance boundary condition on the transmitting and receiving antennas, with electric field $\boldsymbol{E}_z = 1$ on the transmitting antenna and with a source field of zero on the receiving antenna. The low-reflectance boundary to free space is defined as:

$$\boldsymbol{e}_z \cdot \left(\boldsymbol{n} \times \boldsymbol{H} \right) + \boldsymbol{E}_z = 2 \cdot \boldsymbol{E}_{0z}, \tag{3}$$

where $\boldsymbol{H}$ is the magnetic field and $\boldsymbol{E}_{0z} = \boldsymbol{E}_z$ is the electric field.

Because the incoming wave to the domain is propagated parallel to the vertical boundaries and the magnetic field is perpendicular to these boundaries, a perfect magnetic conductor (PMC) boundary condition is used. PMC is defined as:

$$\left(\boldsymbol{n} \times \boldsymbol{H} \right) = 0, \tag{4}$$

where $\boldsymbol{n}$ is a unit vector normal to the boundary.

Fig. 3. The piece of Scots pine that was used in the study

Material and methods

The material chosen for the study was one piece of Scots pine (*Pinus sylvestris*) shown in Fig. 3 with dimensions 40 × 150 × 320 mm. Close to the center of the piece was a cone-shaped knot with a diameter varying from 18 to 25 mm.

A CT scanner (Siemens Somatom) was used to measure the density in the cross sections. The geometric shape, dielectric properties, and moisture distribution in the green condition for each cross section were calculated from the measured density.

Density data from CT scanning was used to calculate variations in the dielectric properties of the wood and of the moisture distribution in the green condition. The difference between CT images in green and dry conditions was calculated and the resulting image was assumed to describe the moisture distribution in the cross section. Cross sections of the piece, as shown in Fig. 4, were scanned with microwaves and CT both parallel and perpendicular to the grain in green and dry conditions.

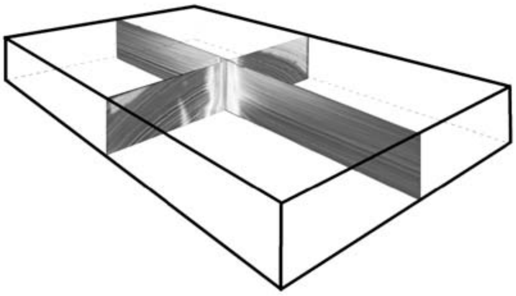

Fig. 4. Two cross sections from the object were scanned. One section was parallel to the grain and the other section was perpendicular to the grain. Regions with low density are darker in the computed tomography (CT) images

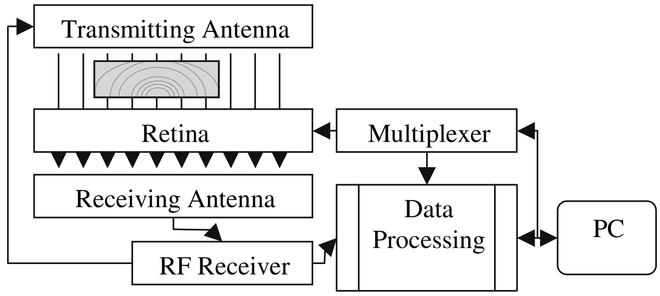

Fig. 6. Sensor system for the microwave scanner. The microwave signal is modulated by a low-frequency signal at 128 probes in the retina. The electromagnetic field at each probe is then extracted from the signal. *RF*, radio frequency; *PC*, personal computer

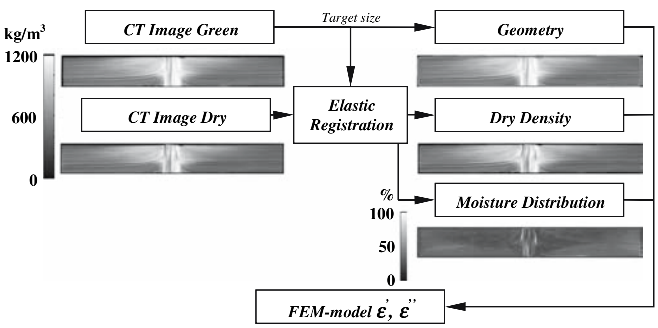

Fig. 5. Brief description of the working procedure in the generation of finite element models

Before the moisture content was calculated from the CT images, it was necessary to compensate the image of dry wood for shrinkage and deformation. Transformation of the CT image of dry wood to the shape of green wood was done by using elastic registration as described by Sorzano et al.[9] Figure 5 shows how the FEM model was generated using density images in green and dry conditions when the electric field (E-field) was oriented perpendicular to the grain (Fig. 4). The same procedure was used when the E-field was parallel to the grain, but the values for ε^* were multiplied with a moisture-dependent factor.[7] Within the knot, the E-field was perpendicular to the grain in both models.

A microwave scanning system described by Johansson[10] that measures attenuation and phase shift of the transmitted electromagnetic field every 8 mm was used for the measurements. Figure 6 shows a schematic drawing on the main part of the system. The wood is illuminated by a quasiplane wave generated by a slotted waveguide that acts as a transmitting antenna where the electrical field is perpendicular to the sensor (9.375 GHz).[11] The wave is locally perturbed at dipoles in the retina by a low frequency signal. This will cause a modulation of the radio frequency (RF) signal that is proportional to the electromagnetic field at the dipoles. This technique, known as modulated scattering technique (MST), has been described by Bolomey and Gardiol[12] among others. The measured values of attenuation and phase shift in the microwave signal after passing through the wood were compared with finite element simulations performed in two dimensions.

Results

The results show that simulated values correspond well to measured values. Figures 7–10 show attenuation and phase angle in the simulated and measured field after transmittance through dry wood. The measured values were obtained by repeated measurements with increasing antenna distance. Figures 11 and 12 show the attenuation when the E-field is oriented perpendicular and parallel to the grain. A clear pattern from the knot in the phase shift for dry wood is shown in Figs. 13 and 14. The phase shift perpendicular to the grain for green wood in Fig. 15 also shows a pattern caused by the knot. The knot is not visible in simulated or measured data for green wood parallel to the grain (Fig. 16).

Discussion

The phase shift is periodic and can only be measured and simulated in the interval $(-\pi, \pi)$. The vectors were unwrapped by changing absolute jumps greater than π to their 2π complement. This only works when the phase shift between adjacent points is less than 2π. The measurements that deviated from the model were attenuation in green wood with the E-field perpendicular to the grain and phase shift in dry wood with the E-field parallel to the grain. The first case can be explained by variations in the z direction. The moisture content was higher on both sides of the scanned cross section. In the second case, the result is very sensitive to changes in the correction factor for permittivity when the E-field is parallel to the grain.

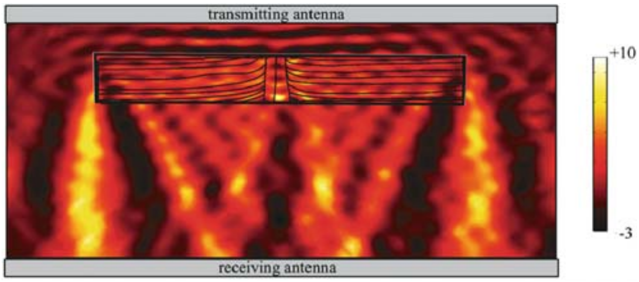

Fig. 7. Simulated attenuation of the electric field (E-field) in dB

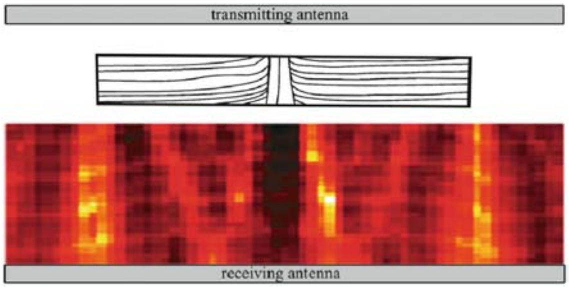

Fig. 8. Measured attenuation of the transmitted E-field

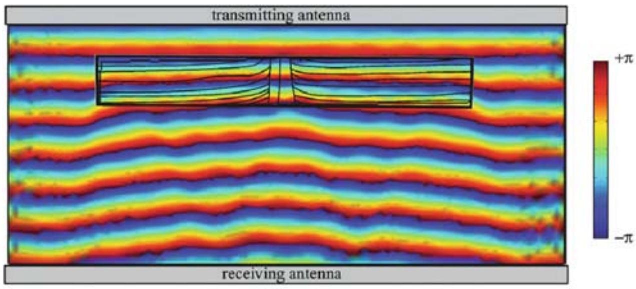

Fig. 9. Simulated phase angle of the E-field in radians

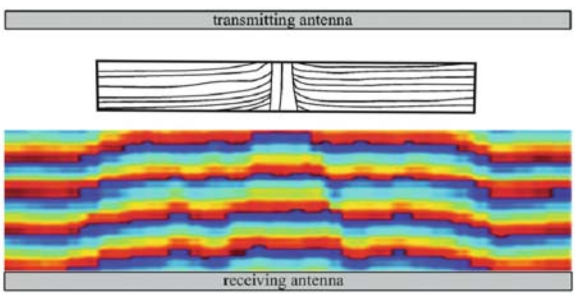

Fig. 10. Measured phase angle of the transmitted E-field

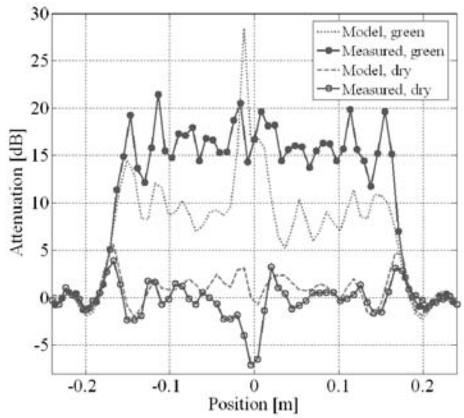

Fig. 11. Simulated and measured attenuation of electromagnetic (EM) wave with the E-field oriented perpendicular to the grain after transmittance through green and dry wood

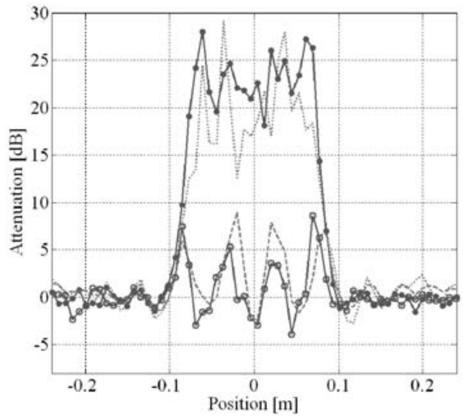

Fig. 12. Simulated and measured attenuation of EM wave with the E-field oriented parallel to the grain after transmittance through green and dry wood

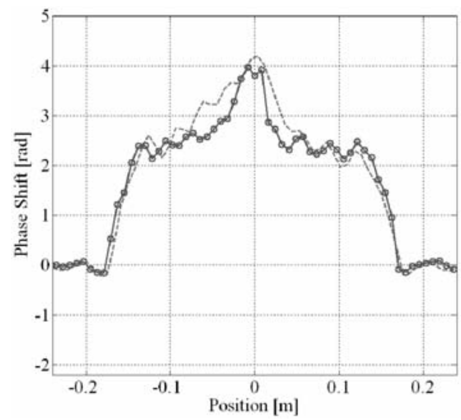

Fig. 13. Simulated and measured phase shift of EM wave with the E-field oriented perpendicular to the grain after transmittance through dry wood

Conclusions

The model corresponds well to the measured values, which show that the FEM simulation could be a useful tool for analyzing microwave scattering in wood. Because wood is an inhomogeneous material, there are discontinuities in density and moisture content in the wood pieces that result in a huge scattering in the measured and simulated values. The greater the discontinuities, the greater is the need for computational power in the simulation. Variations in the z direction give errors if the models are restricted to the xy

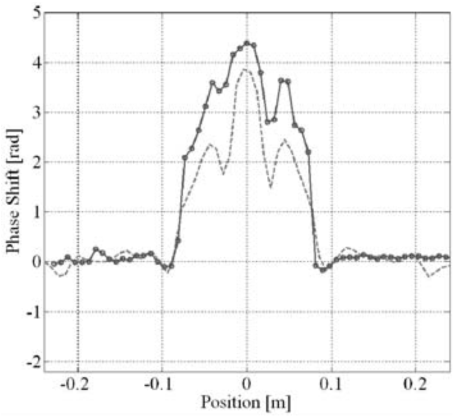

Fig. 14. Simulated and measured phase shift of EM wave with the E-field oriented parallel to the grain after transmittance through dry wood

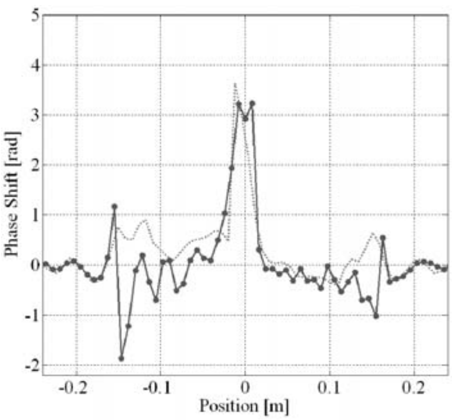

Fig. 15. Simulated and measured phase shift of EM wave with the E-field oriented perpendicular to the grain after transmittance through green wood

plane. The model for dry wood is sensitive to changes in the correction factor for permittivity.

References

1. Johansson J, Hagman O, Fjellner BA (2003) Predicting moisture content and density distribution of Scots pine by microwave scanning of sawn timber. J Wood Sci 49:312–316

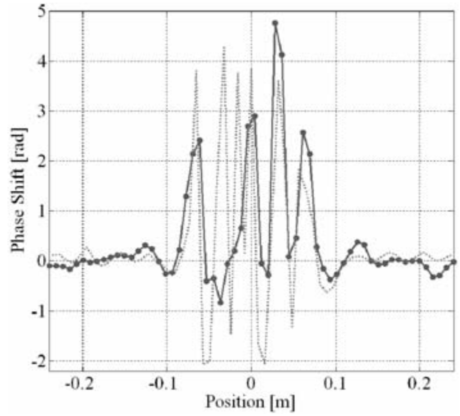

Fig. 16. Simulated and measured phase shift of EM wave with the E-field oriented parallel to the grain after transmittance through green wood

2. Antti L (1999) Heating and drying wood using microwave power. Doctoral Thesis, Luleå University of Technology
3. Perre P, Turner IW (1997) Microwave drying of softwood in an oversized waveguide: theory and experiment. AIChE J 43:2579–2595
4. Zhao H, Turner IW (2000) Use of a coupled computational model for studying the microwave heating of wood. Appl Math Model 24:183–197
5. Lindgren O (1992) Medical CT-scanners for non-destructive wood density and moisture content measurements. Doctoral Thesis, Luleå University of Technology
6. Comsol AB (2005) Comsol home page. http://www.comsol.se. Cited 31 Oct 2005
7. Torgovnikov GI (1993) Dielectric properties of wood and wood-based materials. Springer, Berlin Heidelberg New York
8. Jin J (2002) The finite element method in electromagnetics. Wiley, New York
9. Sorzano COS, Thévenaz P, Unser M (2005) Elastic registration of biological images using vector-spline regularization. IEEE Trans Biomed Eng 52:652–663
10. Johansson J (2001) Property predictions of wood using microwaves. Licentiate Thesis, Luleå University of Technology
11. Satimo France (2005) Satimo home page. http://www.satimo.com. Cited 31 Oct 2005
12. Bolomey JC, Gardiol FE (2001) Engineering applications of the modulated scatterer technique. Artech House, Boston