ESTIMATING WOOD PHYSICAL PROPERTIES BY USING MICROWAVE MEASUREMENTS

by

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B.Sc., Istanbul Technical University, 2002

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
DEPARTMENT OF MECHANICAL ENGINEERING

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
October 2004
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Title of Thesis: Estimating Wood Physical Properties by Using Microwave Measurements

Degree: Master of Applied Science Year: 2004

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Abstract

Wood is a natural material with a wide range of physical properties. For effective use of the material resource, it is important to be able to make reliable non-destructive measurements of material properties. Of particular interest here are grain angle, moisture content and density of wood. These are important for process control and for wood strength estimation.

Microwaves provide an effective method for measuring wood properties. The measurements are non-contact, high speed and safe. Their data content is also very rich, with a total of eight independent measurements at each point. Thus, there is good opportunity for reliable material property evaluation and for data consistency checking. The microwave system described here measures the attenuation and phase change of a microwave beam as it propagates through wood specimens. It makes these measurements for both parallel and perpendicular polarizations. In this study, microwave measurements are made on 76 hemlock and 150 Douglas fir pieces. The collected data are used to estimate the wood grain angle, moisture content and density. For estimations, linear models whose coefficients are calculated by applying least-squares method are constructed. Also, since temperature has a significant influence on electrical properties, the temperature is taken into account as a variable in the formulations.

A significant species dependence was observed in the results, with different moisture and wood density sensitivities for hemlock and Douglas fir. In general, the results from
hemlock were superior to those from Douglas fir. For hemlock and Douglas fir respectively, the standard error of estimation (SEE) of wet density was $4\text{kg/m}^3$ and $10\text{kg/m}^3$ (moisture density range = 40-120 $\text{kg/m}^3$). For dry wood density, the SEE was 40 and 65 $\text{kg/m}^3$ (dry wood density range = 300-650 $\text{kg/m}^3$). For moisture content, the SEE was 1.0% and 2.0% (moisture content range = 6-30%). For grain angles, the SEE was 0.9 and 2.5 degrees (grain angle range = 0-180°). All these results indicate that the microwave method has substantial practical potential as a method for estimating wood moisture density, moisture content and grain angle.
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Acknowledgements

I would like to express thanks to all those who have given me support during this project.

First of all, I would like to thank my supervisor, Dr. Gary Schajer, for giving me the opportunity of working with him on this research project. I am grateful for his suggestions and wisdom that he shared with me, and also for his constant encouragement.

I thank Dr. Mathew Yedlin for his guidance about the microwaves, and Gordon Wright for his help with electrical circuitry. Many thanks to my colleagues, Ali Siadat and Ray Alava, for being very friendly and supportive.

I am also grateful to my roommates, Evren Bai and Nimet Kardes, and my friend Gokhan Suren, it could not be that easy and fun without them. Many thanks to my lovely Megi Senmenek and Fuat Atabey for their hospitality, friendship and courage.

I sincerely thank and express my appreciation to Dr. Philip Evans and the Centre for Advanced Wood Processing for their kind financial support of this research project.

Most important is the support and consideration from my mother, Hasibe Orhan my father, D. Ali Orhan and my sister, D. Duygu Orhan. My special thanks to my darling, Bora Cekyay for his encourage, support and patience. I would have never been able to overcome the difficulties and get through this without them.
Chapter 1

Introduction

Wood is a natural material with a wide range of uses spanning from fine furniture to fuel. Its strength, durability, workability and natural beauty make it an attractive choice in many applications. In North America, a major use for wood is as a construction material, notably dimension lumber for housing construction. This is the application of particular interest here.

Because wood is a natural material, its properties can vary greatly, even within a nominally similar batch of pieces. For example, the strength of lumber pieces may vary by a factor of more than 10, even though they come from the same tree [17]. Thus, it is important to be able to sort the material so that strong lumber is separated for use in load-bearing structures while the weaker pieces are directed to less critical purposes. This matching of the properties of each piece of material to an appropriate application greatly enhances its usefulness and economic value. Thus, effective sorting methods are central to the effective and economical use of the available wood resource.

Grading is the process that is used in industry to separate lumber into different quality classes or grades. There are several methods in use, including visual inspection, bending stiffness measurement and x-ray densitometry. Each method has its particular advantages and limitations; they all are somewhat effective, but they are also far from ideal. It is the objective of this research to develop a microwave sensor for grading wood having
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capabilities that significantly exceed the existing methods. The next paragraphs describe the objectives of lumber grading. They go on to summarize the grading methods commonly used at present, and explain the background and potential of the proposed microwave method.

1.1 Strength Grading

Grade is the basic aspect that controls the value of wood, and depends on both appearance and mechanical strength. Figure 1.1 shows the relationship between the actual strength and the number of pieces within typical batches of mill-run lumber for ungraded pieces. The strength of any individual piece of wood is not known, and a "design strength" is statistically set at a value such that 95% of the pieces have strength at least equal to that value. For structural safety, it is assumed that the strength of each piece equals only the design strength, which is a valid minimum for 95% of the pieces. Any additional strength cannot be guaranteed and is effectively lost.

Figure 1-1: Strength distribution in ungraded samples

Figure 1.1 shows that for the majority of pieces the "lost" strength is substantial. It is clear
that the large majority of the lumber pieces have strengths much greater than the assigned design strength. The median strength is more than double the design strength. The economic value of all the lumber is dragged down to that of the worst pieces and this causes waste of strong pieces and economic value.

![Figure 1-2: Strength distribution of graded samples](image)

With grading, wood is sorted into different classes as shown in Figure 1.2. Each class represents a given level of quality and a commercial value. The middle grade has the same median strength as the ungraded samples in Figure 1.1. However, because the bell curve is narrower, the design strength moves much closer to the median strength and it does not so seriously underestimate the majority of the material. In addition, the very strong material has been promoted into a superior grade with even higher design strength. The material at the low end has been relegated to an inferior grade with a design strength not so much different from the value assigned to the entire batch in Figure 1.1. The utilization efficiency and the economic value of the graded wood are thereby significantly increased. For example, it is estimated that improved lumber strength grading would increase the lumber value by
between 3 and 5% which represents about a $20M annual opportunity in British Columbia [1].

1.2 Strength Grading Methods

Nondestructive evaluation is identification of the physical properties of a material without damaging its end-use properties and using information to make decisions for corresponding usage [3]. Different methods for strength grading of wood have been developed which can be categorized as nondestructive.

1.2.1 Visual Grading

The earliest nondestructive evaluation of wood is visual grading. Lumber is graded by lumber graders. They look at each piece and apply empirical rules to establish its grade. Each structural grade has assigned design strength based on destructive testing of sample batches.

Figure 1-3: Visual Grading [4]
Visual grading is effective for identifying appearance defects such as wane or skip. However, it is much less effective at identifying lumber strength. This is because knot size is used as the main strength criterion, but in reality, it is only one of several strength controlling features [20]. In addition, visual grading is a human process, and it is very strenuous for a grader to examine lumber consistently and comprehensively by eye over long periods.

1.2.2 Bending Stiffness Grading

Mechanical lumber grading methods have been developed to try to reduce the uncertainties and inconsistencies of visually graded lumber. The material produced is called “Machine Stress Rated” (MSR) Lumber. The most common mechanized grading method is based on the regression that stronger lumber tends to have a higher bending stiffness.

The grading process shown in Figure 1.4 involves running the lumber pieces through a series of rollers that successively bend them into a concave and then convex shape. Load cells measure the force required to deflect the wood by a fixed amount, thereby giving the elastic modulus of the material. The average of the concave and convex measurements is used to eliminate the effect of any initial bowing of the lumber [8, 31].

**Figure 1-4:** Schematic illustration of bending stiffness grading method [32]
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MSR grades can be established by measuring the elastic modulus of a large number of lumber pieces, and comparing the results with the strengths determined from destructive tests. Modulus and strength are approximately linearly correlated. Figure 1.5 shows a graph of the actual (destructively measured) strengths vs. predicted (modulus-based) strengths. There is clear trend in the data, but there is also a wide scatter. Regression coefficients $R^2$ are typically in the range 0.5 to 0.6 [20].

![Graph](image)

**Figure 1-5: Lumber strength estimation from bending stiffness grading method**

The modest strength prediction capabilities of the bending stiffness method occur because the measurements do not focus well on the strength controlling features mainly the knots. Typical knots are 1”-2” in diameter, and they are not detected well by the bending stiffness measurements for which the distance between the rollers is 48” [9]. For this reason, MSR lumber is also graded visually as well as mechanically. A further practical concern with the bending stiffness method is the high maintenance costs of the machinery for bending the wood. But despite these issues, MSR lumber is still more consistent than visually graded
lumber. Bending stiffness remains the most common strength grading method.

**1.2.3 X-Ray Grading**

To overcome the limitations of the machine stress grading method, a new method called X-ray grading has recently been developed. X-ray grading has a much finer measurement resolution than bending stiffness grading. It uses a spatial measurement resolution of 1 inch, which is about the same scale as the main strength-controlling features, the knots [20]. Thus, the effect of knots is well represented. In addition, X-ray grading is a non-contact method so maintenance costs are low and service reliability is high.

X-rays coming from a source pass through a piece of lumber, and reach the receivers. During passage through the lumber, a part of the radiation is absorbed by the wood, and the remaining part reaches the receivers. The amount of absorption depends on the density of the part of wood through which the radiation passes [20]. A comparison of measurements of the radiation reaching the receivers with and without wood in place gives the amount of radiation absorbed by the wood. Schematic illustration of the x-ray grading is shown in Figure 1.6.

![Schematic illustration of x-ray grading](image_url)
The local wood density can then be determined directly from these measurements. The density of the clear wood is between 0.4 and 0.6 g/cm$^3$ and the knot wood density changes between 0.8 and 1.2 g/cm$^3$ [24]. Consequently, since knots are twice or more as dense as clear wood, the size of the knots and their locations can be determined within the wood piece. The measured density data is used in algorithms that predict the strength of the material.

![Graph showing predicted versus actual strength](image)

**Figure 1-7:** Lumber strength estimation from strength grading

Figure 1.7 shows the resulting predicted strength graph for the same boards as shown in Figure 1.5. The scatter in the points is much less than previously, indicating significantly improved strength prediction accuracy. The correlation coefficient is increased to around $R^2 \approx 0.7$, indicating the capability to sort tighter, more accurate lumber strength grades [20].

On the other hand, x-ray grading method determines wood strength with respect to the wood density, which is not the only factor that affects it. Since wood is a highly directional material, any change of the grain direction directly and highly affects the strength.
For example, a deviation of just 5 degrees between the grain direction and the main stress direction can reduce the wood strength by as much as 20% [6]. In addition, X-rays require significant safety protections.

1.2.4 Microwave Grading

The use of microwave technology introduces interesting new possibilities for improved wood grading. The microwave technique retains all advantages of the X-ray method, such as measurements for small intervals, non-contacting measurements etc. It has a better interpretation and easier analysis of the signals. In comparison to previous grading methods, microwave measurements have a much richer information content related to wood strength. Basically, they potentially indicate grain (fiber) angle, specific gravity and moisture content, all of which are basic wood quality factors. In addition, the measurement resolution can be sufficiently fine to identify significant strength controlling features. The design and demonstration of a microwave sensor for wood grading is the subject of this thesis.

Determination of physical properties of different materials by using microwaves has been an interesting subject for many researchers. The earliest studies on microwaves were in order to find the moisture content and/or the density of the materials such as wheat, sand, coal, tobacco etc. Scientists developed devices to use microwaves for this purpose [18]. It was found that there was a relationship between these physical properties and the dielectric constants of these materials. The dielectric constant illustrates the dissipating effects such as absorption of energy by the water molecules in the material and is a complex number expressed as $\varepsilon = \varepsilon' - j \varepsilon''$ [10]. The nature of the medium, which the microwave is
propagating in, and its dielectric constant affect the speed and attenuation of microwaves. J.R. King [11] showed that the attenuation, the phase change and the depolarization of microwaves passing through the wood can be measured. Some researchers found that the increase of the dielectric constant is related to the increase of density, moisture content and temperature for frequencies up to 10 GHz, for wood. When the moisture content of wood is below the fiber saturation point, $\varepsilon''$ is less than $\varepsilon'$ [18]. Therefore, the density effect is more significant for $\varepsilon'$ and loss tangent ($\tan \delta = \varepsilon''/\varepsilon'$) is more sensitive to humidity. Thus, it can be said that the variation in the phase of a wave passing through the wood indicates the density. Also, a variation in attenuation of this wave estimates a variation in moisture content [18]. In addition, since wood is an anisotropic material, its dielectric constant changes depending on the direction of the electric field, whether it is parallel or perpendicular to the fibers. Thus, if the plane of the polarized wave is not coinciding with one of the three principal directions of anisotropy, the incident wave is depolarized. This depolarization is used as an indication of the grain angle of the wood [18].

Even though there were successful setups, the microwave grading is not so popular in industry. Thus, it is considered that a new microwave system developed should also be practical for industrial implementation. The advantage of the system introduced here is that it makes several independent measurements of wood electrical properties. The attenuations depend more strongly on moisture content, the propagation delays depend more on specific gravity, and all measurements depend on grain angle [13]. The microwave system can make eight separate electrical measurements, from which five independent dielectric properties are identified. These dielectric properties are in turn used to determine wood moisture content,
specific gravity and grain angle. Also, the instrumentation is not very complicated. All components can be found easily and none of them are expensive. The total cost of the setup is about $10,000. In addition, the microwave system uses 20mW power which is economical and not damaging to the environment. Considering all these, it can be stated that the microwave system described here is a further advance compared to the previous ones.

1.3 Objectives and Overview

The objective of this research is to develop an improved lumber strength grading method using high resolution microwave measurements to estimate wood grain angle, specific gravity and moisture content. The work spans two main areas: (1) development of a practical microwave system, (2) identification of wood physical properties from the microwave data. This thesis covers these two topics, in preparation for the third needed work area that involves using the wood physical properties to identify wood strength. This will be the subject of the future research work.

This work involves the following steps:

(1) Development of a Practical Microwave System

- Design of microwave system that is capable of measuring attenuation and phase delay in two perpendicular planes
- Construction and testing of the system to confirm reliable operation
- Adjustment of design details to minimize the effects of microwave reflections and diffraction
(2) **Identification of wood physical properties from the microwave data**

This work involves the following steps:

- Development of an algorithm to identify principal attenuations, phase delays, and wood grain angle
- Making experimental measurements of attenuation and phase delay using prepared wood samples
- Build a statistical model to identify wood moisture content and specific gravity based on the measured principal attenuations and phase delays
Chapter 2
Microwave Theory

Evaluation of wood physical properties using microwaves is done by measuring the changes in a plane wave that occurs during passage through a wood sample. The main changes of the microwave are attenuation, phase delay and depolarization. These quantities are measured by the microwave system and are used to determine the dielectric properties of the wood. To assist understanding of the measurements described in later chapters, this chapter summarizes the theory of propagation of plane waves through a lossy material such as wood. It goes on to describe the details of attenuation, phase delay and depolarization.

2.1 Microwave Field Theory

The information given in this part is based on the work of Inan and Inan [10].

Microwaves are the common name for electromagnetic waves in the frequency range of 1GHz to 40GHz. Electromagnetic waves consist of time-varying electric and magnetic fields. The most general mathematical framework for classical electromagnetic is described by Maxwell’s equations. In many applications, microwave sources operate within a very narrow band of frequency, so a steady-state sinusoidal approximation is suitable. The time-harmonic (sinusoidal steady state) forms of Maxwell’s equations are listed below with their more general versions where $\bar{e}, \bar{B}, \bar{D}$ and $\bar{H}$ are real (measurable) quantities that vary with time while $E, B, D$ and $H$ are complex phasors that do not vary with time. The relationship between these can be expressed as:

$$\bar{e}(x, y, z, t) = \text{Re} \{E(x, y, z) e^{j\omega t}\}$$
Maxwell’s equations

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]
\[ \nabla \cdot \vec{D} = \rho \]
\[ \nabla \times \vec{H} = \vec{J} + j\omega \vec{D} \]
\[ \nabla \cdot \vec{B} = 0 \]

Time-harmonic Maxwell’s equations

\[ \nabla \times \vec{E} = -j\omega \vec{B} \] (2.1a)
\[ \nabla \cdot \vec{D} = \rho \] (2.1b)
\[ \nabla \times \vec{H} = \vec{J} + j\omega \vec{D} \] (2.1c)
\[ \nabla \cdot \vec{B} = 0 \] (2.1d)

2.2 Propagation in Lossy Media

An ideal medium, vacuum, is lossless, and no absorption of electromagnetic radiation occurs during propagation. On the other hand, in general most dielectric media are “lossy”. They exhibit small but non-zero conductivity or complex permittivity and, can absorb electromagnetic energy; this causes attenuation of an electromagnetic wave as it propagates through the medium.

If conductivity is not equal to zero, \( \sigma \neq 0 \) a conducting current, \( \vec{J}_c = \sigma \vec{E} \), is produced by the electric field of the propagating wave. Because of this current, which is in phase with the electric field, dissipation of some of the wave energy as heat occurs within the material. This dissipation causes the wave electric and magnetic fields to attenuate with distance as they propagate in the lossy material.

The current density is expressed as \( \vec{J} = \vec{J}_{\text{source}} + \vec{J}_c \). In a lossy medium this term does not equal to zero even when there is no source, because of the conducting current \( \vec{J}_c = \sigma \vec{E} \) flowing in response to the wave’s electric field. The current density equation and \( \vec{D} = \varepsilon \vec{E} \)
Chapter 2. Microwave Theory

relations are substituted into Eq. (2.1c).

\[ \nabla \times \mathbf{H} = \sigma \mathbf{E} + j \omega \mathbf{D} \quad (2.2) \]

After taking the curl of Eq. (2.1a), and combining with \( B = \mu H \) and \( \nabla \cdot \mathbf{E} = 0 \), it is found that

\[ \nabla^2 \mathbf{E} - j \omega \mu (\sigma + j \omega \varepsilon) \mathbf{E} = 0 \]

\[ \nabla^2 \mathbf{E} - \gamma^2 \mathbf{E} = 0 \quad (2.3) \]

Eq. (2.3) is called the wave equation, where \( \gamma = \sqrt{j \omega \mu (\sigma + j \omega \varepsilon)} \) is known as the propagation constant (or wave number). In general, it is a complex quantity. Also it can be expressed in terms of its real and imaginary parts as \( \gamma = \alpha + j \beta \). If only the waves propagating in \( z \) direction (all field quantities vary only in \( z \)) with electric field having only an \( x \) component are considered Eq. (2.3) becomes

\[ \frac{d^2 E_x}{dz^2} - \gamma^2 E_x = 0 \quad (2.4) \]

The general solution for Eq. (2.4) is:

\[ E_x(z) = C_1 e^{-\gamma z} + C_2 e^{+\gamma z} = C_1 e^{-\alpha z} e^{-j\beta z} + C_2 e^{+\alpha z} e^{+j\beta z} \]

\[ E_x^+(z) \quad E_x^-(z) \]

\[ (2.5) \]
The wave magnetic field that accompanies this electric field can be found by substituting $E_x(z) = C_1 e^{-\alpha z} e^{-j\beta z}$ into Eq. (2.1a). When $\alpha, \beta$ are both greater than zero, the terms $E^+_x(z)$ and $E^-_x(z)$ represent waves propagating in the $+z$ and $-z$ directions, respectively. If the wave equation expressed in complex phasors is converted to the form expressed in real quantities, it is found that

$$
\varepsilon_x(z,t) = C_1 e^{-\alpha z} \cos(\omega t - \beta z) + C_2 e^{+\alpha z} \cos(\omega t + \beta z)
$$

(2.6)

$C_1$ and $C_2$ are the constants determined by the boundary conditions at material interfaces. The nature of the waves described by the two terms of Eq. (2.6) is shown in Figure 2.1.

![Figure 2-1: Snap shots of waves in a lossy media][10]

As the wave propagates in the $+z$ direction, its amplitude decreases. The attenuation constant $\alpha$ gives the rate of this attenuation. To understand $\alpha$ better, consider two different points one located at $z$ and the other one at $(z+d)$. The distance $d$ between these two points is
constant. The magnitude of the ratio of the electric field at \((z+d)\) to that at point \(z\) is found as;

\[
\frac{E^x_1(z)}{E^x_1(z+d)} = \frac{C_i e^{-\alpha z}}{C_i e^{-\alpha (z+d)}} = e^{\alpha d}
\]

Taking the natural logarithm of both sides gives,

\[
\alpha d = \ln \left( \frac{E^x_1(z)}{E^x_1(z+d)} \right)
\]

The quantity \(\alpha d\) is dimensionless so the unit of \(\alpha\) is \(m^{-1}\) since \(d\) is in meters. However, it is important to mention that \(\alpha d\) is the natural, or Naperian, logarithm of the ratio of the electric fields, \(\alpha d\) usually has a number of nepers. In the context of this conventional usage, \(nepers\) is the unit of the attenuation constant, \(\alpha\). On the other hand, in most engineering applications, a more common unit for attenuation is decibel. Conversion between these units can be given as;

\[
\text{attenuation in decibels (dB)} = 20 \log_{10} \left( \frac{E^x_1(z)}{E^x_1(z+d)} \right)
\]

\[
\text{attenuation in dB} = 20 \log_{10} e^{\alpha d} = (\alpha d)20 \log_{10} e = 8.686[\text{attenuation in nepers}]
\]

\(\beta\) is the phase constant and has unit of \([\text{rad/m}]\). The phase constant determines the
wavelength and the phase velocity of the wave.

The propagation constant, $\gamma$ combines the attenuation constant, $\alpha$ and the phase constant, $\beta$. In earlier sections, the propagation constant was introduced as $\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$. Taking square of both sides and equating the real and the imaginary parts gives

$$\alpha = \omega \sqrt{\frac{\mu \varepsilon}{2}} \left[ \sqrt{1 + \left(\frac{\sigma}{\omega \varepsilon}\right)^2} - 1 \right]^\frac{1}{2} \quad (2.8)$$

$$\beta = \omega \sqrt{\frac{\mu \varepsilon}{2}} \left[ \sqrt{1 + \left(\frac{\sigma}{\omega \varepsilon}\right)^2} + 1 \right]^\frac{1}{2} \quad (2.9)$$

Intrinsic impedance is another quantity that only depends on the material properties of the medium. It is the ratio of the electric and magnetic fields, and has unit of Ohms.

$$\eta_e = |\eta_e| e^{i\delta_e} = \frac{\mu}{\sqrt{\varepsilon - j\frac{\sigma}{\omega}}} \quad (2.10)$$

It can be seen that the attenuation constant $\alpha$, the phase constant $\beta$, and the intrinsic impedance $\eta$, depend sensitively on $\sigma/\omega \varepsilon$. This ratio is called loss tangent, $\tan \delta_e = \sigma/\omega \varepsilon$ and is a measure of the degree to which the medium conducts.
If $\tan \delta_e >> 1$, the medium is considered to be a good conductor. In this case, conductivity, $\sigma$ is much greater than $\omega \varepsilon$ which corresponds to a large attenuation constant and a rapid decay with distance. Also, the intrinsic impedance is very small, approaching to zero as $\sigma \rightarrow \infty$.

If $\tan \delta_e << 1$, the medium is considered to be a poor conductor (good insulator). In this case, $\sigma$ is much less than $\omega \varepsilon$ which corresponds to a small attenuation constant. Also, both of the phase constant and the intrinsic impedance are only slightly different from those for a lossless medium; namely, $\beta = \omega \sqrt{\mu \varepsilon}$ and $\eta = \sqrt{\mu / \varepsilon}$.

The material properties (i.e., $\sigma$ and $\varepsilon$), which plays a very important role in calculations of $\alpha, \beta, \eta$, may be functions frequency. For example, for typical good conductors both $\sigma$ and $\varepsilon$ are nearly independent of frequency, at frequencies below the optical range, but for lossy dielectrics the material constant $\sigma$ and $\varepsilon$ tend to be functions of frequency. The properties of dielectric are usually given in terms of $\varepsilon$ and $\tan \delta_e$.

Lossy dielectrics and good conductors are the two most common cases of practical interest involving the propagation of electromagnetic waves in lossy media. Since wood is a lossy dielectric material, good conductor will not be covered in this thesis.

### 2.3 Propagation in Lossy Dielectrics

When a material is subjected to an electric field, bound charges displace and cause
volume polarization density, \( P \). The charges tend to prevent the polarization \( P \) from keeping in phase with the applied field. The work done against the frictional damping forces causes the applied field to lose power, which is dissipated in the medium as heat. A complex permittivity, \( \epsilon_c = \epsilon' - j \epsilon'' \) characterizes this condition at high frequencies. Also, the material is said to have an effective conductivity, \( \sigma_{\text{eff}} = \omega \epsilon'' \). In general, frequency directly effects both \( \epsilon' \) and \( \epsilon'' \) in complicated ways and the losses in a dielectric depend mostly on the ratio of \( \epsilon''/\epsilon' \). The real part of a material's dielectric constant and its loss tangent identifies its electrical properties. The loss tangent is given as;

\[
\tan \delta_c = \frac{\sigma_{\text{eff}}}{\cos \epsilon} = \frac{\epsilon''}{\epsilon'} \tag{2.11}
\]

In practice, it is not needed to distinguish between losses due to \( \sigma \) and \( \omega \epsilon' \), because \( \epsilon' \) and \( \sigma_{\text{eff}} \) (or \( \tan \delta_c \)) are often determined by measurement.

In most applications, exact expressions of \( \alpha, \beta, \eta \), given by the Eq. (2.8), Eq. (2.9) and Eq. (2.10), are not used because lossy materials can be classified as either good conductor or good dielectric. As mentioned before, if \( \tan \delta_c << 1 \), the material is classified as a good dielectric. For good dielectrics, equations of \( \alpha, \beta \) can be rewritten by using the binomial expression. The binomial expression is applied to the propagation constant equation, then the real and the imaginary parts are equalized to find the attenuation and the phase constants.
\[
\gamma = \alpha + j\beta = j\omega \sqrt{\mu \varepsilon} \left(1 - j \frac{\sigma_{\text{eff}}}{\omega \varepsilon}\right)^{\frac{1}{2}} 
\equiv j\omega \sqrt{\mu \varepsilon} \left[1 - j \frac{\sigma_{\text{eff}}}{2\omega \varepsilon} + \frac{1}{8} \left(\frac{\sigma_{\text{eff}}}{\omega \varepsilon}\right)^2 + \Lambda\right]
\]

\[
\alpha \equiv \frac{\sigma_{\text{eff}}}{2} \sqrt{\frac{\mu}{\varepsilon}} = \frac{\omega \varepsilon}{2} \sqrt{\frac{\mu}{\varepsilon}}
\]

(2.12)

\[
\beta \equiv \omega \sqrt{\mu \varepsilon} \left[1 + \frac{1}{8} \left(\frac{\sigma_{\text{eff}}}{\omega \varepsilon}\right)^2\right] = \omega \sqrt{\mu \varepsilon} \left[1 + \frac{1}{8} \left(\frac{\varepsilon}{\varepsilon}\right)^2\right]
\]

(2.13)

Once more using the binomial expansion, an approximate expression for the intrinsic impedance of a good dielectric can also be obtained.

\[
\eta_e \equiv \sqrt{\frac{\mu}{\varepsilon} \left(1 + j \frac{\sigma_{\text{eff}}}{2\omega \varepsilon}\right)} = \sqrt{\frac{\mu}{\varepsilon} \left(1 + j \frac{\varepsilon}{2 \varepsilon}\right)}
\]

(2.14)

### 2.4 Reflection and Transmission Coefficients

In practice, electromagnetic waves propagate in bounded regions where different media may be present. Regions of different permittivity or regions of different conductivity create the boundary conditions. When a wave reaches the boundary between two homogenous media, it may follow two different behaviors depending on the second medium.

(1) If the second medium is a perfect conductor, within which no electromagnetic field can exist and conductivity is equal to infinity, the incident wave reflects back and there is no transmission to the second medium.
(2) If the second medium is either lossless or lossy, the wave is split into two: a reflected wave propagating back and a transmitted wave going on its way in the second medium.

When properties of the incidence wave and the two media are known, mathematical expressions of the reflected and the transmitted waves can be found by using the Maxwell’s equations with appropriate boundary conditions.

The angle of arrival of the incident wave at a boundary determines the direction and the magnitude of the reflected and the transmitted waves. Since waves are normally incident in our microwave system, oblique incidence will not be covered here. Also, relying on the fact that wood is lossy medium, the reflection and the transmission coefficients will be calculated only for the lossy medium.

2.4.1 Normal Incidence on a Lossy Dielectric

![Diagram of incident, reflected, and transmitted waves](image)

**Figure 2-2:** Incident, reflected and transmitted waves [10]
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When a microwave propagating in medium 1 is normally incident on an interface with a second medium having different dielectric constant, one part of the incident wave is reflected and the other part continues to propagate to the right (+z direction) as shown in Figure 2.2. In the following discussion, the first medium is assumed to be air, which is lossless, and the second medium is a lossy medium.

The phasor fields for the incident, reflected and transmitted waves are given as:

\[ E_i(z) = \hat{x}E_{i0}e^{-j\beta_1 z} \]
\[ H_i(z) = \frac{\hat{y}}{\eta_1} \frac{E_{i0}}{E_{i0}} e^{-j\beta_1 z} \]
\[ E_r(z) = \hat{x}E_{r0}e^{+j\beta_1 z} \]
\[ H_r(z) = -\frac{\hat{y}}{\eta_1} \frac{E_{r0}}{E_{r0}} e^{+j\beta_1 z} \]
\[ E_t(z) = \hat{x}E_{t0}e^{-\gamma_2 z} \]
\[ H_t(z) = \frac{\hat{y}}{\eta_2} \frac{E_{t0}}{E_{t0}} e^{-\gamma_2 z} \]

\( E_{i0}, E_{r0} \) and \( E_{t0} \) are the amplitudes of the incident, reflected and transmitted waves, respectively. To determine the unknowns \( (E_{r0}, E_{t0}) \), two boundary conditions are used: the continuity of the tangential components of both of the electric and magnetic fields across the interface.
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\[ E_i(z = 0) + E_r(z = 0) = E_t(z = 0) \rightarrow E_{i0} + E_{r0} = E_{t0} \]

\[ H_i(z = 0) + H_r(z = 0) = H_t(z = 0) \rightarrow \left( \frac{E_{i0}}{\eta_1} - \frac{E_{r0}}{\eta_1} \right) = \frac{E_{t0}}{\eta_2} \]

The solution of these two equations gives the reflection coefficient, which is defined as the ratio of \( E_{r0} \) to \( E_{i0} \),

\[ \Gamma = \frac{E_{r0}}{E_{i0}} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{2.15} \]

and also the transmission coefficient, which is defined as the ratio of \( E_{t0} \) to \( E_{i0} \),

\[ T = \frac{E_{t0}}{E_{i0}} = \frac{2\eta_2}{\eta_2 + \eta_1} \tag{2.16} \]

In this case, since the first medium is lossless (air), the phase constant and the intrinsic impedance are calculated as \( \beta_1 = \omega \sqrt{\mu_1 \varepsilon_1} \) and \( \eta_1 = \sqrt{\mu_1 / \varepsilon_1} \), respectively. On the other hand, the second medium that is lossy uses the Eq. (2.12), Eq. (2.13) and Eq. (2.14) to calculate the attenuation constant, phase constant and the intrinsic impedance, respectively.

The fact, that the intrinsic impedance for lossy media is complex, results in complex reflection and transmission coefficients. This means, in addition to the differences in amplitudes, phase shifts are also introduced between the incident, reflected and the transmitted fields at interface.
2.4.2 Normal Incidence on Multiple Lossy Dielectrics

In many cases, electromagnetic waves propagate through more than one medium. Inan and Inan [10] model multiple dielectric interface problems as shown in Figure 2.3.

![Figure 2-3: Normal incidence at multiple dielectrics [10]](image)

Their formulations for multiple dielectric interfaces are based on the theory given here. In this case, three different dielectric media are considered having intrinsic impedances \((\eta_1, \eta_2, \eta_3)\) and the boundaries at \(z = -d\) and \(z = 0\). The second medium is assumed to have thickness of \(d\). The problem is treated as a series of reflections, which occur at each interface. Some part of the wave is transmitted into the second medium, which then hits the second boundary and again some part is reflected, other part transmitted to the third medium. After the second reflections, the wave comes back to the first boundary and the sequence continues. Some part of this wave is transmitted to the first medium while the other one goes...
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back towards the second boundary in the second medium. This complicated relationship of the reflected and the transmitted waves does not allow us to use the reflection and the transmission coefficients given previously. However, the way to find these coefficients is still the same, applying the boundary conditions. In the most general form, the expressions for the total wave fields in three media that are shown in Figure 2.3 are given as

Medium 1, $z < -d$

$$E_1(z) = E_{1i} + E_{1r} = \tilde{\chi}E_0 [e^{-j\beta_1(z+d)} + \Gamma_{\text{eff}} e^{+j\beta_1(z+d)}]$$

$$H_1(z) = H_{1i} + H_{1r} = \tilde{\gamma} \frac{E_{10}}{\eta_1} [e^{-j\beta_1(z+d)} - \Gamma_{\text{eff}} e^{+j\beta_1 z}]$$

Medium 2, $-d < z < 0$

$$E_2(z) = E_{2f} + E_{2r} = \tilde{\chi}E_{20} [e^{-\gamma_2 z} + \Gamma_{23} e^{+\gamma_2 z}]$$

$$H_2(z) = H_{2f} + H_{2r} = \tilde{\gamma} \frac{E_{20}}{\eta_2} [e^{-\gamma_2 z} - \Gamma_{23} e^{+\gamma_2 z}]$$

Medium 3, $0 < z$

$$E_3(z) = E_{3f} = \tilde{\chi} T_{\text{eff}} E_{10} e^{-j\beta_3 z}$$

$$H_3(z) = H_{3f} = \tilde{\gamma} \frac{T_{\text{eff}} E_{10}}{\eta_3} e^{-j\beta_3 z}$$

It is important to note that $\Gamma_{23}$ is the reflection coefficient at the interface $z = 0$ while $\Gamma_{\text{eff}}$ is an effective reflection coefficient at the interface $z = -d$ and includes the effect of the
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second medium as well. Similarly, $T_{\text{eff}}$ is an effective transmission coefficient. The equations given above have four unknowns, $E_{20}$, $T_{\text{eff}}$, $\Gamma_{23}$, $\Gamma_{\text{eff}}$, which are determined in terms of the known parameters, $E_{20}$, $\eta_1$, $\eta_2$, $\eta_3$, $\beta_1$, $\gamma_2$, $\beta_3$, by applying the boundary conditions.

At $z = -d$

$$E_{\infty} (1 + \Gamma_{\text{eff}}) = E_{20} (e^{+\gamma_2 d} + \Gamma_{23} e^{-\gamma_2 d}) \quad (2.17a)$$

$$\frac{E_{\infty}}{\eta_1} \left( 1 - \Gamma_{\text{eff}} \right) = \frac{E_{20}}{\eta_2} \left( e^{+\gamma_2 d} - \Gamma_{23} e^{-\gamma_2 d} \right) \quad (2.17b)$$

At $z = 0$

$$E_{20} (1 + \Gamma_{23}) = T_{\text{eff}} E_{\infty} \quad (2.18a)$$

$$\frac{E_{20}}{\eta_2} (1 - \Gamma_{23}) = \frac{T_{\text{eff}}}{\eta_3} E_{\infty} \quad (2.18b)$$

Solutions that are found by using these four equations give the reflection and the transmission coefficients. The main concerns here are the reflections and transmissions through “air-wood-air” configuration. Thus,

$$\Gamma_{23} = \frac{\eta_{\text{air}} - \eta_{\text{wood}}}{\eta_{\text{air}} + \eta_{\text{wood}}} \quad (2.19)$$

$\eta_1$ and $\eta_3$ represent intrinsic impedances of air, and $\eta_2$ intrinsic impedance of wood.

Considering these relations, the transmission and reflection coefficients are formulated as:
Another way of calculating the transmission coefficient is given by Thomson and Tsui [25]. For thickness $d$, they introduce the transmissivity as

\[
T = \frac{T_1 T_2}{(X + R^2 / X - 2RC)}
\]  
(2.22)

where $X = \exp(4\pi kd / \lambda)$, $\phi = \tan^{-1}(2k / (n^2 + k^2 - 1))$, $T_1 = 4 / ((n + 1)^2 + k^2)$, $T_2 = 4(n^2 + k^2) + ((n + 1)^2 + k^2)$, $C = \cos(2\phi + 4\pi md / \lambda)$, $R = ((n - 1)^2 + k^2) / ((n + 1)^2 + k^2)$.

$\lambda$ is the wavelength in free space radiation, $(n + jk)$ is the complex index of transmission where $(n + jk) = (\varepsilon - j \mu)^{1/2}$. $R$ is the reflection coefficient.

Robertson and Buckmaster [19] also use this formulation. They measure transmissivity as a function of the material thickness. Then, an iterative least squares curve fitting program is used to fit Eq. (2.22) to the experimental data. Figure 2.4 and Figure 2.5 reproduce their transmissivity for glass and soft wood. The graphs show how transmissivity
depend on attenuation and reflections.

Figure 2-4: Transmitted power as a function of total thickness for glass [19]

Figure 2-5: Transmitted power as a function of total thickness for soft plywood [19]
Figure 2.4 and Figure 2.5 represent two extreme behaviors. In Figure 2.4, the glass specimen is not very lossy. The attenuation is slow and so reflections dominate and oscillatory behavior occurs. The opposite happens with the wood specimen in Figure 2.5. This material is very lossy, and so attenuation dominates.

Consequently, the transmitted amplitude rapidly decays with only minor oscillatory behavior. If there were no reflections, these two graphs would show smooth decays. As the attenuation decreases, transmissivity graphs become wavier. When the material is wood, approximately exponential attenuation is observed.

The most important difference between these two models used to calculate the transmissivity is the assumption for the reflection coefficient. Inan and Inan [10] introduce the reflection coefficient as a function of thickness, \( d \), which affects it exponentially. The reflection coefficient becomes zero as the thickness goes to zero. On the other hand, Robertson and Buckmaster [19], and Thomson and Tsui [25] assume that the reflection coefficient is independent of material thickness. Neither the first nor the second model is perfectly correct. Likely, the actual behavior is somewhere between them. In this thesis, the first model given by Inan and Inan [10] is used because it gives both attenuation and phase change. In contrast, the second model by Robertson and Buckmaster [19] gives only the attenuation, and not the phase change.

2.5 Polarization and Depolarization of Microwaves

The alignment of the electric field vector of a plane wave relative to the direction of
propagation defines the polarization of the wave. There are three different kinds of polarization: linear, circular and elliptical, Figure 2.6.

A uniform plane wave propagating in the z direction is said to be linearly polarized when it has only one component. Circular polarization consists of two perpendicular plane waves of equal amplitude and 90° difference in phase. Elliptical polarization occurs when two waves have unequal amplitudes and are out of phase by 90°. In our microwave system, a linearly polarized wave passes through the wood piece.

Wood is a strongly anisotropic material, both in its physical strength and in its electrical properties [28]. During the passage of linearly polarized wave through the wood piece, because of the dielectric anisotropy of the wood the wave becomes depolarized [13]. However, depolarization can not be observed if the grain is perfectly parallel or perfectly normal to the incident wave. For example, an incident wave propagating in x direction is divided into y and z components during the passage through the wood if the grain does not lie in the x-y, y-z or z-x planes, as shown in Figure 2.7a [11]. The incident wave’s electric vector is resolved into two components; one in the direction of the maximum dielectric constant and
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the other in the direction of the minimum dielectric constant. Since these two directions have different properties, the new components do not have the same amplitudes and phase changes when they leave the wood piece, depending on the thickness [13]. Thus, the wave emerging from the specimen is effectively elliptically polarized with its minor axis in the direction of the maximum dielectric constant, which is essentially the direction of the grain angle as shown in 2.7b [11].

![Diagram showing two-dimensional grain sloping and elliptical polarization in wood](image)

**Figure 2-7:** a: Two dimensional grain sloping, b: Elliptical polarization in wood [11]

To conclude, while a microwave beam is passing through the wood attenuation, phase delay and depolarization occur because of the anisotropy of the wood. These changes depend on the dielectric properties and the thickness of the sample. Calculations of the dielectric properties will be given in the following chapters.
Chapter 3

Microwave System

The microwave system described here was used to measure the electrical properties of wood.

It consists of a microwave source, a splitter, transmitter and receiver horns with differing planes of polarization, dipoles, an I/Q demodulator, a signal conditioner, a microwave switch.
and a computer. Figure 3.1 schematically shows the microwave apparatus.

The signal from a microwave source is split into two parts. One part is connected directly to the LO part of an I/Q demodulator to provide a phase reference signal. The other part is connected to a double microwave switch with outputs to the two polarizations of a dual polarized transmitter horn. A computer data acquisition system operated the switch, and alternately selected transmission polarizations at 0° or 90° relative to the geometrical axes of the apparatus. A linearly polarized receiver horn was fixed at 45° to the transmitter horn axes so that it could receive components of both transmission polarizations. The received signals were then mixed within an I/Q demodulator with the reference signal from the splitter to give the phase and quadrative components. These were measured by the computer data acquisition system.

A dipole plate was fixed within the area between the horns. This plate contained a pair of modulated dipole scatterers [11]. These dipoles were fixed at 0° and 90° relative to the geometrical axes of the apparatus. Thus, they were parallel and perpendicular to the polarization of the transmitted beams.

The computer read the $I$ and $Q$ signals from the demodulator and identified the components modulated by the dipoles. These components provide the microwave field measurements of the dipole locations.
3.1 Microwave Source and Microwave Switch

The microwave system has a microwave source operated at 10GHz frequency and 20mW power. 10 GHz frequency corresponds to 3cm wavelength, which is a suitable choice for industrial applications. Because it provides a small spatial resolution without excessive phase delays it is difficult to keep track of angles if they are much greater than 360°.

The microwave switch allows the direction of the propagation between two perpendicular directions to change. The switch has one input coming from the microwave source and two outputs to the dual polarized transmitter horn. Depending on the signal sent from the computer, it allows the microwave beam to travel in one of the polarizations. Thus, it is determined whether the polarization will be parallel or perpendicular.

3.2 Transmitter and Receiver Horns

A horn can be used for both transmission and reception of the microwaves. Rectangular, linearly polarized horns with 30dB gain are chosen for both purposes in this microwave system. The transmitter horn used in the system was a square dual polarized horn. The receiver horn was rectangular, with single plane polarization, oriented at 45° to the transmitter horn. The polarization direction of all horns was such that the electric fields were parallel to the input wire. Figure 3.2 shows transmitter horn inputs, direction of electric field and the propagating wave.
The relationship between two horns is very basic; one radiates the microwave beam and the other collects it. However, the significant point is positioning them correctly. The distance between the two horns is important because behavior of the beam changes depending on the field which the receiver horn is placed in. The space around an antenna is divided into three fields: the reacting near field, the radiating near field and the far field, Figure 3.3 [31].
Since the angular field distribution is essentially independent of distance from the source, the receiver horn is placed in far field region. To find the boundary of far field region, frequency, \( f \) and the maximum dimension of the antenna, \( d \) are used in below equations [31]

\[
    r_1 \approx 0.62 \sqrt{\frac{d^2}{\lambda}} \quad r_2 \approx \frac{2d^2}{\lambda} \quad \lambda = \frac{c}{f}
\]

By using \( f = 10GHz \) and \( d = 6cm \), \( r_2 \) is calculated as 28.2 cm. This number represents where the far field starts when measured from the source. Therefore, the transmitter and the receiver horns are placed with a separation between them that is greater than this value, typically about 120 cm.

### 3.3 Dipole Plate

The dipole plate consists of absorber foam, flexible sheet absorber and dipoles, which are placed between two plastic sheets. These pieces are shown separately for clarity in Figure 3.4. In the microwave system they are put together by plastic screws.

![Figure 3-4: Dipole plate components](image)

The plastic sheets are UHMW plastic. Both absorber foam and flexible sheet absorber
are obtained from Emerson & Cuming Microwave Products. The type of the absorber foam is “eccosorb-LS30” and the type of flexible sheet absorber is “CLX-10”.

The dipole plate shown in Figure 3.4 was designed based on the following objectives.

- A sheet of absorber material with one metal coated side is used. This metal coating prevents the direct passage of the microwave beam from the transmitter horn to the receiver horn. A 32mm diameter hole at the center containing the dipoles permits the transmitted signal to be localized to the dipole area.
- The plastic absorber underneath the metal coating reduces reflections between the dipole plate and the receiver horn.
- Although the carbon wires to the dipoles are lossy, they still create a significant modulated signal. It is less damaging for this modulation to be added to the relatively large transmitted signal above the dipole plate, than to the much smaller received signal below the dipole plate. Thus, the carbon wires are placed on the upper surface of the metallized layer. They are covered by microwave absorber foam to reduce the microwave field impugning on them, and also to reduce the modulated signal reflected from them.
- Plastic sheets are placed at the top and bottom surfaces to support and protect the interior components.

Since it is desired to modulate the local microwave field in the direction of the dipoles, scattering components are placed on the other side of the sample from radiation. These components consist of a part of dipoles with a diode at each of their centers, Figure 3.5 [11].
Bias currents are provided through carbon wires connected to the ends of the dipoles. The high resistance of these wires (1-5 kΩ/cm) makes them very lossy, so they do not substantially reflect the ambient microwave radiation. The dipoles are made of two metallic parts connected by a diode. The total length is 1.9cm, which is about \( \lambda/2 \) for the 10GHz microwave radiation. When the diode is forward biased the two halves of the dipole are electrically joined together to give an effective length of about \( \lambda/2 \), which cause strong reflections of the local microwave field. However, when the diode is reversed biased, the dipole is electrically disconnected into two \( \lambda/4 \) parts, which do not cause strong reflections of the local microwave field. Thus, modulation of the dipoles on and off causes corresponding modulations in the received microwave signals. The size of these received modulations is proportional to the electric field strength of the microwave field at the dipole.

### 3.4 Challenges

The two most persistent problems with the microwave system are reflection and diffraction of microwave beams. These effects occur at all surfaces and edges exposed to the
microwave beam. To reduce these effects, absorber foam which is the same kind used in the dipole plate was placed within the dipole plate and on top of the wood samples. Each absorber foam sheet had a circular hole at the center, coaxial with the dipoles. By a process and error, it was found that the most artifact-free measurements were obtained when the absorber foam on top of the wood was highly absorbing (98%) with a hole 102 mm diameter for the large wood pieces; 76 mm diameter for the small pieces during the measurements. Positioning of the absorber foam on the wood piece is given in Figure 3.6.

![Figure 3-6: Wood piece and the absorber foam; a: front view, b: top view](image)

Placing the wood piece underneath the absorber foam is a solution not only for the reflections but also for the diffraction problem. When a microwave hits the edges of the wood piece, it follows such a way that can not be defined as either reflection or transmission, edge diffraction [22]. Covering the dipole plate and the wood piece with an absorber foam having a hole in the center, eliminates this problem but introduces a new one; aperture diffraction. It cannot be avoided that a wave bends around an aperture and spreads out in a circular wave [35]. However, since the size of the size of aperture determines the effect of diffraction [22], by using a sufficiently large hole (diameter > 2λ), this problem can be solved or at least its effects can be reduced.
In the measurement part, the wood pieces used can be divided into two groups with respect to their sizes. One group has pieces having dimensions of (140x140x38) mm and the other (89x89x38) mm. For least effect of reflection and diffraction problems, the aperture diameters were chosen to be slightly smaller than the dimension of the wood samples.

To summarize, the conditions that must be satisfied for solution or reduction of the reflection and diffractions problems are (1) The diameter of the circular hole at the center of the absorber foam must be chosen such a way that all edges and the corners of the wood piece must be covered, due to the reflections and edge diffraction, (2) The hole diameter can neither be close to the size of wavelength nor smaller than it due to the aperture diffraction, and (3) The absorber foam must have high amount of absorption to reduce or completely eliminate the reflections and diffractions.
Chapter 4

Properties of Wood

Wood is a natural material with a complex structure. It consists of hollow, tubular cells that grow parallel to each other. These cells are mostly slender and pointed at the ends. Figure 4.1 shows the principal cells of soft wood.

![Figure 4-1: Three dimensional appearance of small cube of wood, Sitka spruce X75](image)

The cell or “grain” direction is one of the three principal axes defined by the cylindrical geometry of the tree. The longitudinal axis is parallel to the grain, the radial axis is perpendicular to the grain in the radial direction, and also it is normal to the growth rings, and the tangential axis is perpendicular to the grain but tangent to the growth rings. These three axes where wood has greatly different properties in are shown in Figure 4.2 [6].
Unlike materials having homogeneous structure, wood shows different mechanical properties in longitudinal, radial and tangential axes because of its anisotropic behavior [27]. For structural applications, the most important characteristics of the wood is its strength. Therefore, it is important to estimate wood strength reliably. It is known that physical properties of wood such as grain angle, moisture content and specific gravity have important effects on wood strength. One way of calculating the wood strength is using its physical properties [13]. The main aim of this thesis is calculating these three physical properties of wood. Finding the strength will be a subject for a further research.

This thesis deals with microwave grading for two main purposes: measurement of electrical properties of wood and calculation of physical properties of wood. However, the electrical properties, attenuation, phase delay and depolarization, are only of intermediate interest here. The ultimate interest is in the wood physical properties: grain angle, moisture content and specific gravity. The challenge is to determine how to estimate these physical properties from the various measurements of electrical properties.
This chapter summarizes physical properties of wood and their effects on wood strength, electrical properties of wood, relationships between these two and mathematical formulations used to calculate one from the other.

4.1 Physical Properties of Wood

The most important three physical properties of wood that have significant effect on wood strength are grain angle, moisture content and specific gravity. Definitions of these properties and their relations to the strength will be given in this section.

4.1.1 Grain Angle

For wood, the term "grain" is defined as the direction of the wood fibers relative to the axis of the tree or the longitudinal edges of a piece of cut lumber [6]. Because of the knots, grain distortions occur [21]. A knot is the portion of a branch that is embodied into the stem of the tree. A living branch produces a knot that connects with the surrounding wood, and produces an “intergrown’ knot. In contrast, a dead branch behaves as if it were a nail driven into the tree trunk. It is disconnected from the surrounding wood, and is usually encased in a thin layer of bark [27].

The knot itself is a visible weakness, but the wood around it is also weak, although less obviously. The effect of a knot is bigger than it looks. The influence of a knot on mechanical properties of wood is due to the interruption of continuity and change in the direction of wood fibers associated with the knot [5]. Strength of wood is reduced due to the appearance of knots because; a knot replaces clear wood with wood whose grain is oriented in the perpendicular (weak) direction. Also, it disturbs the fiber orientation around it,
resulting in grain distortion [5]. Because of the distorted fibers, large stress concentrations occur. Firstly, the type of knot affects the amount of reduction in strength. Intergrown knots produce greater deviations of fibers in wood while encased knots behave as absence or discontinuity of wood material. Thus, intergrown knots have a more important influence on wood strength than encased ones [6, 27]. The amount of reduced strength is also dependent on both the location and the size of the knot within the wood piece. For example, a knot on the top or bottom edge of wood piece has much larger influence than the same knot placed near the center line [2].

In addition, as knot size increases, the distortion of the grain around the knot increases as well, thus the strength decreases [2]. The reduction in strength is more than proportional when compared to the increase of the knot size, as it is seen in Table 4.1.

**Table 4.1:** Strength reduction in lumber resulting from knots as shown in ASTM Standard D 245 [2]

<table>
<thead>
<tr>
<th>Knot diameter: mm (in)</th>
<th>Beam depth: Beam depth: mm (in)</th>
<th>90 (3.5)</th>
<th>140 (5.5)</th>
<th>185 (7.25)</th>
<th>235 (9.25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (1)</td>
<td></td>
<td>25</td>
<td>16</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>51 (2)</td>
<td></td>
<td>51</td>
<td>33</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>76 (3)</td>
<td></td>
<td>na</td>
<td>50</td>
<td>37</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Knot diameter: mm (in)</th>
<th>Beam depth: mm (in)</th>
<th>90 (3.5)</th>
<th>140 (5.5)</th>
<th>185 (7.25)</th>
<th>235 (9.25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (1)</td>
<td>43</td>
<td>30</td>
<td>23</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>51 (2)</td>
<td>81</td>
<td>55</td>
<td>43</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>76 (3)</td>
<td>na</td>
<td>79</td>
<td>63</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>
Another factor that has an influence on the amount of strength reduction caused by the knots is the type of loading. The effect of a knot on strength is more in tension than in compression. In bending, position of the knot whether it is in compression or tension side of beam considerably influences the strength [27].

Variation in strength properties of wood with respect to the grain angle can be explained with a Hankinson-type formula, which can be expressed graphically as shown in Figure 4.3 [6].

If there were no grain deviation, the grain angle would be equal to zero and grain direction would be like the dashed line showed on Figure 4.4a. In this case, the strength of wood would be 100%, no reduction. However, as the grain angle increases, the strength of wood drops rapidly, Figure 4.3. When grain angle reaches 90 degrees, the strength is reduced to

![Figure 4-3: Effect of grain deviation on strength (Hankinson-type formula) [6]](image-url)
about 5%. The decrease in strength with respect to the grain distortion is not proportional. For example, a grain distortion about 15 degrees, shown on Figure 4.4a, halves the strength as shown in Figure 4.3.

![Figure 4-4: a: knot on an old tree and grain distortion, b: knot on a new tree](image)

A fresh lumber specimen such as Figure 4.4b does not fully reveal the extent of the grain distortion. A weathered specimen shows the grain distortion more clearly because the wood has cracked along the grain directions caused by the knots, Figure 4.4a.

**Table 4-2:** Strength reduction in lumber resulting from slope of grain as shown in ASTM Standard D 245 [2]

<table>
<thead>
<tr>
<th>Slope of grain ratio</th>
<th>Bending</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 in 6</td>
<td>60</td>
<td>44</td>
</tr>
<tr>
<td>1 in 8</td>
<td>47</td>
<td>34</td>
</tr>
<tr>
<td>1 in 10</td>
<td>39</td>
<td>26</td>
</tr>
<tr>
<td>1 in 15</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>1 in 20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Grain deviation affects tensile strength more seriously than compressive strength and bending strength reduction is intermediate [27]. The percent of strength loss in bending and compression due to the grain deviation is shown in Table 4.2.

4.1.2 Moisture Content

Water naturally exists in all parts of a living tree and affects almost all properties of wood and wood products. The only case when wood contains no moisture in it is when it is kept in an oven above 100°C (oven-dried). Depending on the environment where wood is placed, wood takes on or loses moisture. Moisture content of any wood is expressed as the ratio of weight of water contained in wood to the weight of oven dry wood in percent. Moisture content range is between about 30% and about 200%, dry basis, in trees [6].

Moisture is stored in two ways in wood cells: water in cell cavities is called “Free water”. “Absorbed water” is bounded to the cell walls. When compared to the bound water, it is easier to move the free water. Therefore, free water is the first one that leaves the wood when it is drying. Since there is a surface adsorption within the wood structure, bound water is held more tightly and removed secondly. Also, as the moisture content decreases below the FSP, the bond between the water and wood becomes tighter. When wood begins losing water during drying the amount of water in the cell walls remains the same, until the free water is completely evaporated. “The Fiber Saturation Point” is the critical point at which evaporation of free water finishes and cell walls start losing water. Fiber saturation point of wood is about 30% moisture content [6]. The importance of fiber saturation point is because of its effect on wood properties. Below the fiber saturation point, the physical and the mechanical properties
of wood begin to change with respect to moisture content [28]. As the moisture content drops most elastic and strength properties of wood increase. This increase is because of the changes in wood cell walls, which become more stiffly connected. Thus, wood becomes stronger. The effect of moisture content change on wood properties is not the same for all properties. For example, a 1% change of moisture content increases the strength in axial compression 6%, bending strength 5%, hardness 2.5-4%, modulus of elasticity 2% etc. Toughness is the only exception since it is not increased with decrease of moisture content [2, 28].

![Diagram](image)

**Figure 4-5:** Relation between strength and moisture content of small clear specimens of Sitka spruce [29]
Figure 4.5 shows the relation of strength properties to moisture content of Sitka spruce pieces.

### 4.1.3 Specific Gravity

Specific gravity is an important physical property that controls the weight of wood. Specific gravity and density are both directly related to most of the mechanical and physical properties of wood. These two terms describe the mass of wood per unit volume. However, density is defined as the mass contained in a unit volume of a material while specific gravity is the ratio of the density of the material to the density of water. Therefore, density is expressed in kilograms per cubic meter (kg/m$^3$) or pounds per cubic foot (lb/ft$^3$) and specific gravity is unitless since it is a ratio. To prevent confusion while considering or comparing different species, instead of density specific gravity is used. Also, to reduce any ambiguity, specific gravity of wood is calculated with respect to the oven-dry weight and volume for specific moisture content.

Moisture content and structure are two main factors affecting specific gravity. Above the fiber saturation point, specific gravity of wood that is based on oven-dry weight does not change because the volume remains constant. Below the fiber saturation point, an increase of specific gravity is observed due to the decrease in volume [2]. The relationship between the moisture content and specific gravity is given in Figure 4.6.
Secondly, structure of wood influences the specific gravity since composition of cell walls and cell cavities create the wood. Their amounts determine the specific gravity of wood. Therefore, some species have more wood substance than the others which means they have higher relative specific gravities [2]. Thus, specific gravity can be considered as a very good index of the amount of wood substance in a wood piece.

Specific gravity is the best index of clear wood strength. As the specific gravity increases, wood becomes denser and therefore, strength increases as well. The relationship of specific gravity and strength are not the same for different species but it is linear almost for
all of them [27]. Also, the changes of specific gravity do not have the same influence on different mechanical properties.

![Figure 4-7: Relations of strength (y), and density (x): 1, static bending; 2, axial compression; 3, hardness. (Based on European and North American species) [27]](image)

Figure 4.7 shows some strength-specific gravity relationships for different mechanical properties. It should be noted that these are average relationships. There are wide strength variations for different wood species and for different samples within the same species.

### 4.2 Electrical Properties of Wood

The dielectric constant, $\varepsilon'$ and the loss factor, $\varepsilon''$ together identify the electrical properties of wood [26]. The dielectric constant is a measure of amount of electric field energy stored in a volume of material in comparison to a vacuum. The amount of electric
field energy transferred to thermal energy within a volume of material is expressed as the loss factor [26]. The dielectric constant and the loss factor are used to define two important terms: the dielectric permittivity, \( \varepsilon = \varepsilon' - j\varepsilon'' \), and the loss tangent, \( \tan \delta_c = \frac{\varepsilon''}{\varepsilon'} \). More detailed information about these two terms is given in Chapter 2.

Temperature, tree species, density, and orientation of electric field vector affect the dielectric properties of wood [26]. Since temperature strongly affects the dielectric properties of water, it also considerably influences the dielectric properties of moist wood. The critical temperature is 0°C. At temperatures below 0°C, temperature decrease causes reduction both in the dielectric constant and in the loss tangent of wood [26]. On the other hand, below 0°C, water is found in two forms at the same time: it can occur in as frozen free water or as unfrozen bound water. The ratio of these two forms determines the dielectric properties of wood at any sub-zero temperature [26]. This behavior was taken into account while choosing the temperatures for the experiments. The dielectric properties are different for different tree species. This difference can be observed on the properties in longitudinal direction more than on the ones in tangential direction. When electric field vector is parallel to the fiber direction, \( \varepsilon' \) and \( \tan \delta_c \) become the biggest if any other conditions is the same [11].

The dielectric properties provide a useful understanding of wood structure. They also offer a way to determine the physical properties of wood. Attenuation, phase change and depolarization, which are the electrical properties used to calculate the physical properties, are dependent on the dielectric properties. Since wood is an orthotropic material, the dielectric properties of wood are different in directions parallel and perpendicular to the
grain. Consequently, the attenuation, phase change and depolarization also depend on the angle between the wood grain direction and the microwave electric field.

![Diagram of microwave beams in air and wood](image)

**Figure 4-8:** Two microwave beams, one traveling in air and the other in wood

As a microwave beam passes through a wood specimen, some of its properties are altered [12]. Figure 4.8 represents two microwave beams, one traveling in air and the other in wood. In the beginning, before the second beam enters wood pieces, both of them have amplitude of $A_0$. Since air is a lossless medium at microwave frequencies, its amplitude does not change during the passage.

On the other hand, a lossy medium such as wood has some other effects on microwave beams. Due to the energy absorption in wood during the passage, decrease in amplitude of the beam is observed [13]. The ratio of the two amplitudes, $A_0$ and $A_1$, gives the
attenuation which is shown as $\Delta A$. The difference between these two amplitudes can easily be seen in Figure 4.8. Amplitude of the beam is not the only thing that changes while the beam propagates in the wood piece. In addition, wavelength and speed of the propagation decrease as well [13]. Phase change, shown in Figure 4.8 as $\Delta \phi$, reflects both of these retardations, which are related to each other. Both of attenuation and phase change that occur in wood are directly related to the moisture content and the specific gravity of wood [14]. Details of these relationships are given in Section 4.3.

**Figure 4-9:** Microwave beams traveling in different directions; a: perpendicular, b: parallel, c: random
The two main directions considered for wood are parallel and perpendicular directions to the fiber direction. The microwave beam can be traveling in either parallel or perpendicular directions when it reaches wood piece. In both conditions, as shown in Figure 4.9a and Figure 4.9b, the beam leaves the wood pieces in the same direction that it entered. Even though attenuation and phase change occur during the passage, direction of travel is still the same after it leaves wood.

On the other hand, the microwave beam can also enter in a completely different direction, neither parallel nor perpendicular. In this case, beam is divided into its components in parallel and perpendicular directions after entrance. When the beam leaves the wood pieces, its components come together again. The beam coming out from the wood piece does not travel in the same direction that it comes in, Figure 4.9c. What happened in wood is depolarization of the microwave beam due to the anisotropy of wood [13]. The important point is that depolarization occurs in the directions of the grain thus, it indicates the grain angle of wood.

4.3 Relations of Electrical and Physical Properties of Wood

In this thesis, the main interest is in estimating wood moisture content, specific gravity and grain angle. This is done by measuring electrical properties, attenuation and phase change. For this purpose, the microwave system described in Chapter 3 is used. The details of how attenuation and phase change measurements are related to establish the wood physical properties are described in this section.
Microwaves coming from the transmitter horn can propagate in two mutually perpendicular directions, arbitrarily called polarization 1 and polarization 2. The electric field vector, $\vec{E}$, can be in the same direction as either dipole 1 or dipole 2. When the electric field vector is parallel to dipole 1, corresponding to polarization 1, attenuation and phase change measurements are taken from both dipoles. This makes four measurements, two from dipole 1 and two from dipole 2. In addition, when electric field vector is parallel to dipole 2, which corresponds to polarization 2, similarly four more measurements are taken from two dipoles, two from each. Thus, there are a total of eight electrical measurements from which principal attenuation and principal phase quantities will be calculated in order to find the physical properties of wood.

To be able to calculate attenuation and phase change for four cases, which are combinations of polarization and dipoles, amplitudes and phases are measured without wood and with wood as well. Figure 4.10 shows all directions for measurements very clearly where, $\vec{X}$, $\vec{Y}$ represent the transmitter directions,
$X, Y$ represent the receiver directions,

$x, y$ represent the wood grain directions,

$\theta$ is the grain angle from $X$ to the wood grain direction.

For convenience, the measured values are indicated with letters as follows;

1) when there is no wood

$A_X$: component of $\bar{X}$ received by receiver $X$, (polarization 1 and dipole 1)

$A_Y$: component of $\bar{X}$ received by receiver $Y$, (polarization 1 and dipole 2)

$B_X$: component of $\bar{Y}$ received by receiver $X$, (polarization 2 and dipole 1)

$B_Y$: component of $\bar{Y}$ received by receiver $Y$, (polarization 2 and dipole 2)

2) when there is wood

$C_X$: component of $\bar{X}$ received by receiver $X$, (polarization 1 and dipole 1)

$C_Y$: component of $\bar{X}$ received by receiver $Y$, (polarization 1 and dipole 2)

$D_X$: component of $\bar{Y}$ received by receiver $X$, (polarization 2 and dipole 1)

$D_Y$: component of $\bar{Y}$ received by receiver $Y$, (polarization 2 and dipole 2)

It is important to remember that all these are complex numbers where real part represents attenuation and the imaginary part represents phase.

Polarization directions and dipole positions are shown on Figure 4.11. Upper planes can be thought as if placed just under the receiver horn, and the other two planes at the bottom are assumed as the dipole plate.
Let “u” and “v” be equal to complex attenuations parallel and perpendicular to the wood grain, and $\theta$ the angle from the $X$ axis to the wood grain direction. The initial measurements are without any wood present. First the $X$ transmitter is active, corresponding to polarization 1. If there is no wood, what is received in $X$ direction (dipole 1) is equal to that transmitted in $X$ direction. In this case, measured value is $A_x$. Similarly, what is received in $Y$ direction (dipole 2) is equal to that transmitted in $Y$ direction and measured value is $A_y$. According to $X$ and $Y$ axes, those two components can be shown as:

$$A_x = A_x \cos \theta + A_y \sin \theta$$, transmitted in $x$ direction

$$A_y = -A_x \sin \theta + A_y \cos \theta$$, transmitted in $y$ direction

When wood is placed between the transmitter and receiver horns, the microwave beam is resolved into its components because of the wood anisotropy. After passing through the
wood, components of the microwave beam are altered because of the wood. Therefore, what is received in \(x\) and \(y\) directions are not \(A_x\) and \(A_y\). These changes are expressed by multiplication \(A_x\) and \(A_y\) by \("u"\) and \("v"\), respectively.

\[
C_x = u A_x = u(A_x \cos \theta + A_y \sin \theta), \text{ received in } x \text{ direction}
\]

\[
C_y = v A_y = v(-A_x \sin \theta + A_y \cos \theta), \text{ received in } y \text{ direction}
\]

In the \(X\) and \(Y\) directions, the received values in \(X\) and \(Y\) are

\[
C_X = C_x \cos \theta - C_y \sin \theta, \text{ received in } X \text{ direction}
\]

\[
C_Y = C_x \sin \theta + C_y \cos \theta, \text{ received in } Y \text{ direction}
\]

When \(C_x\) and \(C_y\) are substituted into the last two equations, it is found that;

\[
C_X = A_X (u \cos^2 \theta + v \sin^2 \theta) + A_Y (u - v) \sin \theta \cos \theta \tag{4.1}
\]

\[
C_Y = A_X (u - v) \sin \theta \cos \theta + A_Y (u \cos^2 \theta + v \sin^2 \theta) \tag{4.2}
\]

Secondly, same steps are followed for the case when only \(\bar{Y}\) transmitter is active. Empty field readings are \(B_X\) and \(B_Y\) and received values in \(X\) and \(Y\) are given as;

\[
D_X = B_X (u \cos^2 \theta + v \sin^2 \theta) + B_Y (u - v) \sin \theta \cos \theta \tag{4.3}
\]
Eq. (4.1), Eq. (4.2), Eq. (4.3) and Eq. (4.4) are rearranged to solve for $u$, $v$ and $\theta$.

\[
D_y = D_x (u - v) \sin \theta \cos \theta + D_y (u \cos^2 \theta + v \sin^2 \theta) \tag{4.4}
\]

\[
p = \frac{B_x C_x - B_x C_y - A_x D_x + A_x D_y}{A_x D_x - B_x A_y} \tag{4.5}
\]

\[
q = \frac{B_y C_x + B_x C_y - A_y D_x - A_y D_y}{A_x D_x - B_x A_y} \tag{4.6}
\]

\[
t = \frac{-B_x C_x + B_y C_y + A_x D_x - A_y D_y}{A_x D_x - B_x A_y} \tag{4.7}
\]

where, $p = u + v$, $q = (u - v) \cos 2\theta$, $t = (u - v) \sin 2\theta$. The complex principal attentions and the wood grain angle are found as;

\[
u, v = \frac{p \pm \sqrt{q^2 + t^2}}{2} \tag{4.8}
\]

\[
\theta = \frac{\arctan(-\text{real}(t)/\text{real}(q))}{2} \tag{4.9}
\]

The magnitudes and the angles of calculated “$u$” and “$v$” represent the microwave beam’s principal attentuations, $\Delta A$ and the principal phase changes, $\Delta \phi$ in the two
orthogonal directions, respectively. Both moisture content and specific gravity affect attenuation, $A$ and phase, $\phi$ of microwaves propagating through the wood [15]. Therefore, the changes $\Delta A$ and $\Delta \phi$ are used to determine the moisture content and the specific gravity of wood.

King and Basuel [14], and Kraszewski and Kulinski [16] use a linear interpretive model to determine moisture content and specific gravity, which is originally a work of Kraszewski [15]. They define moisture content as the ratio of water weight to total weight of material. In the simplest case, it is assumed that the relation of $\Delta A$ and $\Delta \phi$ to weight of water and weight of dry piece is linear [15]. Models for attenuation and phase change are given as:

$$\Delta A = W_w a_1 + W_d a_2$$

$$\Delta \phi = W_w a_3 + W_d a_4$$

where $W_w$ is the basis weight of water in material and $W_d$ is the basis weight of dry material. $a_1, a_2, a_3, a_4$ are numerical coefficients that are found by using the least squares method.

In this thesis, moisture content equation is defined as the ratio of the weight of water in material to the weight of dry material, which is the general formulation for wood and wood-based materials.
Unlike Kraszewski’s model [16], the relations between $\Delta A$, $\Delta \phi$ and $W_d, W_w$ are expressed here in inverse format. $W_d, W_w$ are moved to the left side of the equations while $\Delta A$ and $\Delta \phi$ are put on the right side. Thus, Eq. (4.10) and Eq. (4.11) become

$$W_w = \Delta A b_1 + \Delta \phi b_2 \quad (4.13)$$

$$W_d = \Delta A b_3 + \Delta \phi b_4 \quad (4.14)$$

Two sets of data are available from the parallel complex attenuation “$u$” and the perpendicular complex attenuation “$v$”. Therefore, calculation of basis weights with respect to the attenuation and the phase changes can be done in several different ways. This provides the opportunity to get a more accurate result. The analysis can be done by using only parallel data, only perpendicular data and combination of them. When parallel and perpendicular data are considered separately, following formulations can be used to calculate the wet and dry basis weights for parallel and perpendicular directions.

$$(W_w)_{parallel} = \Delta A_{par} b_1 + \Delta \phi_{par} b_2 \quad (4.15)$$

$$(W_d)_{parallel} = \Delta A_{par} b_3 + \Delta \phi_{par} b_4 \quad (4.16)$$
Another way of calculating basis weights is combining parallel and perpendicular data. Thus, instead of having two wet and dry basis weights for each direction, one wet and one dry basis weight is found for the wood piece.

\[
(W_w)_{\text{perpendicular}} = \Delta A_{\text{perp}} b_5 + \Delta \phi_{\text{perp}} b_6 \quad (4.17)
\]

\[
(W_d)_{\text{perpendicular}} = \Delta A_{\text{perp}} b_7 + \Delta \phi_{\text{perp}} b_8 \quad (4.18)
\]

Both of these formulations end up with totally 8 constants. To reduce the number of constants, a third formulation can be introduced.

\[
W_w = \Delta A_{\text{ave}} c_1 + \Delta \phi_{\text{ave}} c_2 + \Delta A_{\text{perp}} c_3 + \Delta \phi_{\text{perp}} c_4 \quad (4.19)
\]

\[
W_d = \Delta A_{\text{ave}} c_5 + \Delta \phi_{\text{ave}} c_6 + \Delta A_{\text{perp}} c_7 + \Delta \phi_{\text{perp}} c_8 \quad (4.20)
\]

where \(\Delta A_{\text{ave}} = (\Delta A_{\text{par}} + \Delta A_{\text{perp}})/2\) and \(\Delta \phi_{\text{ave}} = (\Delta \phi_{\text{par}} + \Delta \phi_{\text{perp}})/2\). It is important to note that none of the coefficient groups is the same since they are all coming from different sets of data. From measured values of \(W_d\), \(W_w\), \(\Delta A_{\text{ave}}\) and \(\Delta \phi_{\text{ave}}\) numerical coefficients are
found. Then, substituting these coefficients back into the equations provides the basic equations used to calculate wet and dry basis weights of a wood piece when attenuation and phase change of a microwave passing through this piece is known. By comparing the standard errors of $W_d$ and $W_w$ for all three formulations, the best one among them will be chosen to be used in analysis.

Moisture content can be found by taking the ratio of calculated of $W_w$ to $W_d$, as shown in Eq. (4.12). Alternatively, moisture content can be estimated directly using the measured data. Like $W_w$ and $W_d$ formulations, moisture content can be estimated from separate analysis of parallel and perpendicular data or a combination of them. On the other hand, unlike $W_w$ and $W_d$ formulations, effects of attenuation and phase change on moisture content are not introduced by separate constants. Therefore, moisture content is defined as based on the ratio of attenuation to phase change, instead of having them separately.

$$
(mc)_{parallel} = \frac{\Delta A_{par}}{\Delta \phi_{par}} b_9 + b_{10} \tag{4.23}
$$

$$
(mc)_{perpendicular} = \frac{\Delta A_{perp}}{\Delta \phi_{perp}} b_1 + b_{12} \tag{4.24}
$$

$$
mc = \frac{\Delta A_{ave}}{\Delta \phi_{ave}} d_s + d_6 \tag{4.25}
$$
Based on Eq. (4.25), some similar formulations can be derived such as;

$$mc = \frac{\Delta \phi_{ave}}{\Delta A_{ave}} d_7 + d_8$$  \hspace{1cm} (4.26)

$$mc = \frac{\Delta A_{ave}}{\Delta \phi_{ave}} d_9 + \frac{\Delta \phi_{ave}}{\Delta A_{ave}} d_{10} + d_{11}$$  \hspace{1cm} (4.27)

Again, after the analysis the one with the smaller standard error will be chosen for the further steps. Density is the total weight of a material divided by its volume and basis mass is the ratio of weight of material to its area, so density can be expressed as basis weight divided by thickness. Wet and dry densities are given as;

$$\rho_w = \frac{W_w}{t} \text{ and } \rho_d = \frac{W_d}{t}$$  \hspace{1cm} (4.28)

To summarize, during the passage of a microwave beam through wood piece attenuation, phase change and depolarization of the microwave beam occur. These three electrical properties of wood are the keys for finding its physical properties, which are grain angle, moisture content and density. Attenuation and phase change predominantly affect moisture content and density while depolarization reflects grain angle. The advantage of the system used here is that it provides data for two different directions. Therefore, analysis of these data separately and together gives the opportunity of getting more accurate results.
Chapter 5
Measurements and Results

In the microwave system schematically shown in Figure 4.1, the outputs I and Q from the I/Q demodulator respectively represent the magnitudes of the components of the received signal that are in phase and in quadrature with the reference signal.

Each I and Q together make a measurement corresponding to a complex number. In the complex plane, “I” represents the real axis and “Q” does the imaginary axis.

Figure 5-1: Relationship between I and Q

“\( A \)” denotes the amplitude, \( A = \sqrt{I^2 + Q^2} \) and “\( \theta \)” denotes the phase, \( \tan \theta = Q/I \).

5.1 Calibrating the Equipment

An ideal I/Q demodulator would give outputs I and Q having exactly equal amplitudes with 90° phase shift between them. Figure 5.2 shows plots of I and Q measured with the actual I/Q demodulator changing the relative phase using a phase shifter. In the figure, it can be seen that amplitudes of I and Q are far from being equal. Therefore, measurements taken from the microwave system need to be calibrated.
For the practical application, it is important that the $I$ and $Q$ signals have equal magnitude and a $90^\circ$ phase shift relative to each other. Their absolute magnitudes are not important because all attenuation measurements are normalized relative to “open field” measurements with no wood present. Likewise, the absolute phases are not important because all phase delay measurements are calculated as phase differences. Thus, there is no loss of generality if it is assumed that the signal $I$ is “correct”. It then remains to adjust signal $Q$ so that it has equal magnitude and $90^\circ$ phase difference.

\[ I = S \sin \psi + C \cos \psi \quad (5.1) \]

\[ Q = S_q \sin \psi + C_q \cos \psi \quad (5.2) \]
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The constants $S_i, C_i, S_q, C_q$ were found using least-square analysis of the data in Figure 5.2.

With these constants new definitions of $I$ and $Q$ are created:

\[ I = A_i \sin(\psi + \phi_i) \]  
\[ Q = A_q \sin(\psi + \phi_q) \]

where $A_i = \sqrt{S_i^2 + C_i^2}$, $\tan \phi_i = C_i / S_i$ and $A_q = \sqrt{S_q^2 + C_q^2}$, $\tan \phi_q = C_q / S_q$.

Choosing $I$ as the reference, $Q$ is expressed as following.

\[ I = A \sin \theta \]  
\[ Q = \alpha A \sin(\theta + \phi) \]

"$A_i$" is set to "$A$" and "$\psi + \phi_i$" is set to "$\theta$" where $\alpha = A_q / A_i$ and $\phi = \phi_q - \phi_i$. From (5.5) and (5.6), $\sin \theta$ and $\cos \theta$ are determined as follows.

\[ \sin \theta = I / A \text{ and } \cos \theta = \frac{Q - \alpha \sin \phi I}{\alpha A \cos \phi} \]

\[ \tan \theta = \frac{\alpha \cos \phi I}{Q - \alpha \sin \phi I} \]

(5.7)
Also, again by using (5.5) and (5.6), amplitude “$A$” is formulated as

$$A = \sqrt{I^2 + \left( \frac{Q - \alpha \sin \phi I}{\alpha A \cos \phi} \right)^2}$$  \hspace{1cm} (5.8)

Eq. (5.7) and Eq. (5.8) show the “corrected” amplitude and the phase results from the set of imperfect measurements of $I$ and $Q$ in Figure 5.2.

To find the most efficient $\alpha$ and $\phi$ values, it is set that $\alpha = 1$ and $\phi = \pi / 2$, which are the values for an “ideal” I/Q demodulator. Formulations are applied to the data in Figure 5.2, from which the best fit values $\alpha = 1.376$ and $\phi = 1.794$ rad were found. Figure 5.3 is a plot of the “corrected” $I/Q$ values from Eq. (5.5) and Eq. (5.6).
5.2 Understanding the Nature of Measurements

To understand the nature of the measurements some basic attenuation and phase change measurements were made. For these tests, eleven MDF (Medium Density Fiberboard) pieces with (152 x 152 x 19) mm dimensions were used. The particular reason for choosing MDF pieces is that they are not directional like natural wood [34]. Thus, attenuation and phase change measurements can be observed independent of the effect of directional properties. Each piece was weighed and its basis weight calculated. Microwave readings were made as the MDF pieces were added one by one into the microwave system, as shown in Figure 5.4

![Figure 5-4: Horns, dipole plate and MDF pieces, front view](image)

Attenuation is calculated by dividing the amplitude at that time by the empty field amplitude. Phase change for each piece is the difference between the phase value and the empty field phase. Phase change is adjusted by subtracting 360° when needed to avoid phase wrapping. To see how close these measurements were to the reality, the expected values of attenuation and phase change are also calculated. Attenuation is expected to be exponential
and phase delay linear.

\[
\text{attenuation} = \exp(A \times \text{basis weight})
\]
\[
\text{phase change} = B \times \text{basis weight}
\]

where \(A\) and \(B\) are constants. After calculating the regressed values of attenuation and phase change based on the formulation given above, the errors between the measured and regressed values are calculated. The mean value of the attenuation errors is 0.01 and, the mean value of the phase delay errors is 2.1 degrees.

Figure 5.5 and Figure 5.6 show attenuation vs. basis weight and phase change vs. basis weight graphs, respectively. In both graphs, each dot shows the measured value when one MDF piece is added into the microwave system. The lines represent the regressed values. The sinusoidal deviation in the attenuation graph is caused by diffraction and internal reflections. Also, when Figure 5.5 is compared to Figure 2.5 that is obtained by Thompson and Tsui [25], it can be seen that both of the graphs have very similar behavior. Therefore, as well as the very low attenuation error, this comparison supports the idea that these measurements are realistic. The measured phase change values fit on the regressed line well.

Consequently, since both errors are low and, both measured attenuation and phase change values fit on the regressed ones, it can be said that the measurements taken from the system are logical and can be used for the further steps.
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Figure 5-5: Measured and regressed attenuations by using MDF pieces

Figure 5-6: Measured and regressed phase changes by using MDF pieces
5.3 Principal Attenuation and Principal Phase Lag Calculations

Because of the fiber structure, wood has different properties parallel and perpendicular to the grain directions [6]. It is convenient to base physical property calculations on these principal directions. Therefore, before estimating grain angle, moisture content and specific gravity, principal properties must be found correctly, independent of wood orientation. Here, the principal attenuation and principal phase lag formulations given in Chapter 4, are used to calculate the principal properties. To investigate this, the following experiment setup was used. The wood piece was placed on a rotating table that was driven by a stepper motor, as shown in Figure 5.7.

![Experiment setup, side view](image)

**Figure 5-7**: Experiment setup, side view

Attenuation and phase delay measurements were made at a sequence of wood orientations at 5° intervals in the range 0-180°. No further information is available beyond this range because the responses repeat in 180° cycles. At each angular position, the $I$ and $Q$ signals from each dipole are measured for each transmitted polarizations, a total of eight measurements. From these measurements, and the corresponding “open field” measurements,
the various attenuations and phase delays can be calculated.

Figure 5.8 shows the attenuation and phase measurements. The four curves are

P1D1: polarization 1, dipole 1, (x),

P1D2: polarization 1, dipole 2, (+),

P2D1: polarization 2, dipole 1, (☑),

P2D2: polarization 2, dipole 2, (◊).

The first two curves show the attenuation or phase delay in each of the transmitter directions. The curves change between the two principal values, recognized as a local maximum or minimum. These principal values are 90° apart, corresponding to the angle between the wood principal directions. The second two curves show the cross-axis
measurements. For example “P1D2” indicates the signal corresponding to dipole 2, polarization 1 measurement. Since the transmitted polarization and the dipole are perpendicular to each other, the received signal should be close to zero. This occurs when a wood principal direction corresponds to a transmitter polarization direction. However, when the directions do not correspond, depolarization occurs, and signals are received. As shown in Figure 5.8, the “cross-axis” signals vary from zero at 0° and 90°, to a maximum when the axis directions are 45° apart.

Another way of considering the attenuation and phase delay caused by the presence of wood is to draw a phase plane. This diagram consists of an x-y plot of the real and imaginary parts of the complex attenuation. In this diagram, the radial vector corresponds to the amplitude attenuation. The angle from the real axis corresponds to the phase. Figure 5.9 shows an example phase plane.

![Phase Plane Diagram](image)

**Figure 5-9:** Complex attenuations for a range of grain directions, a: on axis measurements, b: cross-axis measurements. 1 = parallel, 2 = perpendicular

Points 1 and 2 correspond to the two principal complex attenuations. It may be shown that for a perfectly aligned microwaves system, the complex attenuations for intermediate
directions lie along a straight line between points 1 and 2. It may further be shown that the cross-axis measurements lie along a parallel line of the same length, centered on the origin.

Figure 5.10 shows an example set of experimental measurements. For the measurements, alignment of the polarization directions with the dipoles plays an important role. It was not possible to align them perfectly and small deviations are unavoidable. However, these deviations are not harmful; the formulation in Section 4.3 takes them into account.

For each of the measured data, plotted in the previous graphs, principal attenuation and principal phase are calculated by using the formulation given in Section 4.3. The calculated principal properties for each measurement are given in Figures 5.11 and 5.12.
Figure 5-11: Parallel and perpendicular principal attenuations

Figure 5-12: Parallel and perpendicular phase lags
As it can be seen from the graphs, the calculated principal properties give straight lines. This desirable result means that instead of making 37 measurements, just one from any direction is enough for accurate calculations. The measurements at any intermediate angle give substantially the same results.

5.4 Physical Property Measurements and Results

To estimate the physical properties of wood, the formulations of grain angle, moisture content and specific gravity given in Chapter 4 are used. The data to be used in those formulations are obtained from testing three different groups of wood samples having different amounts of water in them.

1- 76 hemlock pieces with dimension of (89 x 89 x 38) mm
2- 78 Douglas fir pieces with dimension of (89 x 89 x 38) mm
3- 72 Douglas fir pieces with dimension of (140 x 140 x 38) mm

Since temperature is known to influence wood electrical properties [26], to observe this influence on estimating wood physical properties wood samples are subjected to temperature changes during the measurements. Wood pieces are stored in three different places: in a refrigerator, in an ice box and in the laboratory. Corresponding temperature ranges are named as cold, cool and room temperature, respectively. These three ranges temperature are within

1- Cold (between 0°C to 8°C),
2- Cool (between 12°C to 17°C),
3- Room temperature (between 24°C to 28°C).
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The temperature ranges are limited between 0°C and 28°C. Because of the laboratory test limitation, the highest temperature was 28°C. The lower limit was chosen as 0°C to avoid freezing conditions [26].

Wood pieces are moved from one environment to the other for temperature changes. Since moisture in air at three different environments and in the wood piece are not equal, the pieces are sealed in ziplock bags to prevent any moisture exchange. Pieces are kept in their new position at least 24 hours because a shorter period would not be enough for inner parts of the piece to increase or decrease to the new temperature. After the resting period, the temperature of the sample was measured immediately before testing. The temperature was sensed by a thermocouple that was inserted into a small hole in the corner of the piece. Since the surface of the wood cools faster than the inner part, the hole depth was chosen as about half of the wood piece thickness. Also, the small hole diameter was chosen to be only slightly larger than the thermocouple pin diameter is to prevent air transfer into the hole and affect temperature measurements.

Thus, each physical property is calculated for nine different groups. Each wood piece was weighed before testing. After completion of the microwave complex attenuation tests at the three temperature ranges, each piece was dried in an oven at about 104°C and then weighed again. Hence, before starting the analysis total and dry weights of the wood piece and weight of water are known. When all measurements are completed, data files containing principal attenuations and principal phase changes, wet and dry weights were prepared.
Chapter 5. Measurements and Results

The last check that is done before the analysis is checking the relationships between the parallel and perpendicular principal properties. The purpose of this check was to guard against erroneous points. These would appear as obviously outlying points in the group. Following examples are chosen from hemlock and small Douglas fir pieces. Both for attenuation and phase, the relation between the parallel and perpendicular polarizations is linear. All measured points groups together nicely, providing the linear relationship.

![Graph showing parallel and perpendicular attenuations of hemlock pieces at cold group](image)

**Figure 5-13:** Parallel and perpendicular attenuations of hemlock pieces at cold group
Chapter 5. Measurements and Results

Figure 5-14: Parallel and perpendicular phase changes of hemlock pieces at cold group

Figure 5-15: Parallel and perpendicular attenuations of small D. fir pieces at cold group
5.4.1 Grain Angle

The physical property of wood that is calculated first is the grain angle. The actual grain angle is identified by rotation of the wood piece by a stepper motor. The predicted grain angle is computed from Eq. (4.9). In the perfect case, the relation between the actual and the predicted grain angle should be exactly linear. Although the graphs obtained from grain angle prediction are not perfect linear lines, they are close to being linear. Figure 5.17 gives an example of the estimations. The aim of the dashed line on the graph is to show the best fit to the data. Sometimes, wood pieces may have and initial grain angle which is observed as the gap at the zero point. Another reason for this gap may be the misalignment of the dipoles. The number appearing on the upper left corner of the graph is the standard error of the grain angle prediction for the tested wood piece.
When all wood samples are considered, including three species and three temperatures, it is found that the standard error of grain angle varies between 0.5 and 4.5 degrees. Since the measurements were taken over a wide range of samples at different temperatures, standard errors of actual and predicted grain angles of 27 randomly chosen pieces 3 from each of the nine groups are given in Table 5.1.

**Table 5-1**: Grain angle standard errors for randomly chosen wood samples

<table>
<thead>
<tr>
<th>Species</th>
<th>Std. error, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemlock</td>
<td>0.9</td>
</tr>
<tr>
<td>small Douglas fir</td>
<td>3.5</td>
</tr>
<tr>
<td>big Douglas fir</td>
<td>2</td>
</tr>
</tbody>
</table>
5.4.2 Specific Gravity

Wet and dry basis weights are based on three different formulations. The first formulation, based on Eq. (4.15), Eq. (4.16), Eq. (4.17) and Eq. (4.18), is eliminated since it considers parallel and perpendicular cases separately and requires eight coefficients. Even though both of the other two formulations combines parallel and perpendicular data, the second one, referring to equations 4.19 and 4.20, is dependent on eight constants as well while the third one, indicated by Eq. (4.21) and Eq. (4.22), needs just four coefficients. Because the third formulation halves the number of coefficients needed, it is the preferred choice. Dividing basis weight by the thickness gives the density. Since the aim here is to estimate density, Eq. (4.21) and Eq. (4.22) are modified as

\[ \rho_w = \Delta A_{ave} \frac{e_1}{t} + \Delta \phi_{ave} \frac{e_2}{t} \]  \hspace{1cm} (5.9)

\[ \rho_d = \Delta A_{ave} \frac{e_3}{t} + \Delta \phi_{ave} \frac{e_4}{t} \]  \hspace{1cm} (5.3)

where \( \rho_w \) and \( \rho_d \) refers to the wet and the dry densities, respectively and \( t \) is the thickness of the wood piece. The matrix algebra containing actual wet density and principal properties gives coefficients \( e_1, e_2 \), and similarly, \( e_3, e_4 \) are calculated with respect to actual dry density and principal properties. All calculations are done using MATLAB. The calculated coefficients are given in Table 5.2, Table 5.3 and Table 5.4 for all cases.
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| Table 5-2: Wet density formulation coefficients of hemlock pieces |
|-------------------|-------|-------|-------|
| $e_1$              | -0.049| -0.041| -0.028|
| $e_2$              | -0.004| -0.004| -0.004|
| $e_3$              | 0.434 | 0.414 | -0.412|
| $e_4$              | -0.050| -0.049| -0.049|

| Table 5-3: Wet density formulation coefficients of small Douglas fir pieces |
|-------------------|-------|-------|-------|
| $e_1$              | -0.042| -0.034| -0.054|
| $e_2$              | -0.004| -0.004| -0.003|
| $e_3$              | 0.702 | 0.574 | 0.334 |
| $e_4$              | -0.057| -0.052| -0.043|

| Table 5-4: Wet density formulation coefficients of big Douglas fir pieces |
|-------------------|-------|-------|-------|
| $e_1$              | -0.074| -0.069| -0.049|
| $e_2$              | 0.000 | 0.000 | -0.002|
| $e_3$              | 0.345 | 0.421 | 0.566 |
| $e_4$              | -0.06 | -0.065| -0.073|

When the coefficients are determined, they are substituted back into Eq. (5.9) and Eq. (5.10). Then, $\rho_w$ and $\rho_d$ are estimated from these equations by using measured principal properties. Data from Figure 5.18 to Figure 5.20 indicate the relations between the actual and the predicted wet densities obtained from Eq. (5.9) for each group of wood samples.
Hemlock pieces

(a) "cold"

\[
SEE = 4.59 \text{kg/m}^3
\]

(b) "cool"

\[
SEE = 3.99 \text{kg/m}^3
\]
Figure 5-18: Hemlock wet density [kg/m³], a: cold, b: cool, c: room temperature

Small Douglas fir pieces
Figure 5-19: Small Douglas fir wet density [kg/m³], a: cold, b: cool, c: room temperature
Big Douglas fir pieces

(a) "cold"

\[ \text{SEE} = 12.91 \text{ kg/m}^3 \]

(b) "cool"

\[ \text{SEE} = 5.91 \text{ kg/m}^3 \]
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Figure 5-20: Big Douglas fir wet density [kg/m$^3$], a: cold, b: cool, c: room temperature

Table 5-5: Wet density standard errors of three wood groups

<table>
<thead>
<tr>
<th>Std. error, kg/m$^3$</th>
<th>cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemlock</td>
<td>4.59</td>
<td>3.99</td>
<td>3.30</td>
</tr>
<tr>
<td>small Douglas fir</td>
<td>9.66</td>
<td>7.35</td>
<td>10.94</td>
</tr>
<tr>
<td>big Douglas fir</td>
<td>12.91</td>
<td>5.91</td>
<td>7.33</td>
</tr>
</tbody>
</table>

The standard errors between the predicted and actual wet densities are given in Table 5.5 for three groups at three temperature ranges. Among the three groups, hemlock pieces give the lowest standard error. Although Douglas fir pieces have higher standard errors, considering the graphs, it can be said that the formulation created results able to predict the wet density of wood. Likewise, from Figure 5.21 to Figure 5.23 show the relation between the actual and predicted dry densities obtained from Eq. (5.10).
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Hemlock Pieces

(a) "cold"
SEE = 13.76 kg/m³

(b) "cool"
SEE = 15.39 kg/m³
Figure 5-21: Hemlock dry density [kg/m³], a: cold, b: cool, c: room temperature

Small Douglas fir pieces
Figure 5-22: Small Douglas fir dry density [kg/m$^3$], a: cold, b: cool, c: room temperature
Big Douglas fir pieces

(a) "cold"

\[ SEE = 35.16 \text{ kg/m}^3 \]

(b) "cool"

\[ SEE = 37.22 \text{ kg/m}^3 \]
Table 5-6: Dry density standard errors of three wood groups

<table>
<thead>
<tr>
<th>Std. error, kg/m³</th>
<th>cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemlock</td>
<td>13.76</td>
<td>15.39</td>
<td>20.00</td>
</tr>
<tr>
<td>small Douglas fir</td>
<td>90.75</td>
<td>101.68</td>
<td>79.41</td>
</tr>
<tr>
<td>big Douglas fir</td>
<td>35.16</td>
<td>37.22</td>
<td>45.84</td>
</tr>
</tbody>
</table>

Standard errors of dry density estimation are given in Table 5.6. Like wet density, hemlock pieces give the best results among three groups. However, for dry density prediction the difference between the wood species is not negligible. An unexpected behavior is observed for small Douglas fir species. Big Douglas fir pieces do not have the bending shape in the graphs but the obtained results are scattered. Therefore, although dry density prediction method works well for hemlock pieces, it is not so good for Douglas fir pieces.
5.4.3 Moisture Content

To be able have an idea how accurately moisture content is estimated from measured data, actual moisture content of each piece is also calculated. The actual moisture content is found by dividing the actual weight of water to the actual dry weight of the wood piece. In Chapter 4, formulations to estimate the moisture content are introduced in four different ways. The first one corresponding to Eq. (4.23) and Eq. (4.24) results in two moisture content values, one for parallel and the other for perpendicular directions, for the same wood piece. Also, this method needs four coefficients, which can be reduced by the other three formulations. The other three methods that are indicated by Eq. (4.25), Eq. (4.26) and Eq. (4.27) are all based on the sum of the parallel and perpendicular attenuation and phase change values, instead of considering them separately. The best formulation among these three is chosen by comparing the standard errors between the actual and the predicted moisture contents. In addition, consistency of the constants in the equations plays an important role in determining the most suitable formulation. The moisture content standard errors of the hemlock pieces at three different conditions are given in Table 5.7. Similarly, Tables 5.8 and Table 5.9 are for small and big Douglas fir pieces, respectively. These standard errors are similar in size with those found with conventional capacitance-type moisture meters [23, 30, 7].

**Table 5-7: Moisture content standard errors of hemlock pieces**

<table>
<thead>
<tr>
<th>Std. error, %</th>
<th>cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. (4.25)</td>
<td>1.18</td>
<td>0.94</td>
<td>1.05</td>
</tr>
<tr>
<td>Eq. (4.26)</td>
<td>1.29</td>
<td>1.08</td>
<td>1.12</td>
</tr>
<tr>
<td>Eq. (4.27)</td>
<td>1.17</td>
<td>0.93</td>
<td>1.02</td>
</tr>
</tbody>
</table>
Table 5-8: Moisture content standard errors of small Douglas fir pieces

<table>
<thead>
<tr>
<th>Std. error, %</th>
<th>cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. (4.25)</td>
<td>2.59</td>
<td>2.36</td>
<td>1.75</td>
</tr>
<tr>
<td>Eq. (4.26)</td>
<td>2.55</td>
<td>2.32</td>
<td>2.28</td>
</tr>
<tr>
<td>Eq. (4.27)</td>
<td>2.55</td>
<td>2.31</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Table 5-9: Moisture content standard errors of big Douglas pieces

<table>
<thead>
<tr>
<th>Std. error, %</th>
<th>Cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. (4.25)</td>
<td>3.01</td>
<td>1.96</td>
<td>1.49</td>
</tr>
<tr>
<td>Eq. (4.26)</td>
<td>3.03</td>
<td>1.99</td>
<td>1.62</td>
</tr>
<tr>
<td>Eq. (4.27)</td>
<td>3.01</td>
<td>1.95</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Comparison of those nine standard error groups indicates that the standard errors are similar for all three equations. However, applying the last formulation ends up with three coefficients while the first two have two. The use of fewer coefficients gives a more robust solution. Eq. (4.25) gives slightly better results compared to Eq. (4.26), and so it is the chosen formulation. The chosen formulation is:

\[ mc = \frac{\Delta A_{\text{ave}}}{\Delta \phi_{\text{ave}}} e_5 + e_6 \]  

(5.11)

The behavior of wood is different for different species at different temperatures, so constants \( e_5 \) and \( e_6 \) are determined for all nine groups.

Table 5-10: Coefficients used in moisture content formulation of hemlock pieces

<table>
<thead>
<tr>
<th>coefficients</th>
<th>fridge</th>
<th>ice box</th>
<th>laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_5 )</td>
<td>404</td>
<td>393</td>
<td>397</td>
</tr>
<tr>
<td>( e_6 )</td>
<td>2.36</td>
<td>0.71</td>
<td>-0.98</td>
</tr>
</tbody>
</table>
Table 5-11: Coefficients used in moisture content formulation of small D. fir pieces

<table>
<thead>
<tr>
<th>coefficients</th>
<th>fridge</th>
<th>ice box</th>
<th>laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_5$</td>
<td>499</td>
<td>384</td>
<td>322</td>
</tr>
<tr>
<td>$e_6$</td>
<td>-1.46</td>
<td>1.38</td>
<td>3.09</td>
</tr>
</tbody>
</table>

Table 5-12: Coefficients used in moisture content formulation of big D. fir pieces

<table>
<thead>
<tr>
<th>coefficients</th>
<th>fridge</th>
<th>ice box</th>
<th>laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_5$</td>
<td>329</td>
<td>379</td>
<td>342</td>
</tr>
<tr>
<td>$e_6$</td>
<td>-7.41</td>
<td>-11.05</td>
<td>-8.48</td>
</tr>
</tbody>
</table>

Table 5.10, Table 5.11 and Table 5.12 give computed $e_5, e_6$ values for those nine groups. The measured principal attenuation and principal phase change values and the constants $e_5$ and $e_6$ are used to estimate moisture content for every piece. The following figures display the relations between the predicted and the actual moisture contents for nine groups.

**Hemlock pieces**

![Graph showing predicted vs. actual moisture content for hemlock pieces](image_url)
Figure 5-24: Hemlock moisture content [%], a: cold, b: cool, c: room temperature
Chapter 5. Measurements and Results

Small Douglas fir pieces

(a) cold

$SEE = 2.59\%$

(b) cool

$SEE = 2.34\%$
Figure 5-25: Small Douglas fir moisture content [%], a: cold, b: cool, c: room temperature

Big Douglas fir pieces
Figure 5-26: Big Douglas fir moisture content, a: cold, b: cool, c: room temperature
Chapter 5. Measurements and Results

Correlation coefficients are given on each graph. For these nine graphs, the standard errors are given in Table 5.13

Table 5-13: Moisture content standard errors of three wood groups

<table>
<thead>
<tr>
<th>Std. errors, %</th>
<th>cold</th>
<th>cool</th>
<th>room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemlock</td>
<td>1.18</td>
<td>0.94</td>
<td>1.05</td>
</tr>
<tr>
<td>small Douglas fir</td>
<td>2.59</td>
<td>2.34</td>
<td>1.75</td>
</tr>
<tr>
<td>big Douglas fir</td>
<td>3.01</td>
<td>1.96</td>
<td>1.49</td>
</tr>
</tbody>
</table>

If three groups are compared in terms of the standard errors and moisture content graphs, hemlock pieces give the best results. Hemlock moisture content is estimated with about 1% error, which is low. The graphs obtained from the data collected from laboratory temperature range are more compact and have smaller standard error values than fridge and ice box measurements. This may be due to the temperature variations. All measurements were not taken in one day so the room temperature was not constant during measurements. Therefore, the change in room temperature may affect the pieces when they come out from the fridge or the ice box. On the other hand, the third group of pieces is not affected since they have been conditioned at room temperature.

5.5 Temperature Measurements and Results

Moisture content and density were calculated for three temperature ranges, excluding the temperature effect in section 5.4.2 and section 5.4.3. The purpose in this section is to find formulations that consider the temperature as a variable. In the beginning, moisture content and density formulations including temperature are guessed as;
Chapter 5. Measurements and Results

\[ \rho_w = \Delta A_{ave} (e_{11} + e_{12} T) + \Delta \phi_{ave} (e_{22} + e_{22} T) \]  
\[ (5.12) \]

\[ \rho_d = \Delta A_{ave} (e_{33} + e_{33} T) + \Delta \phi_{ave} (e_{44} + e_{44} T) \]  
\[ (5.13) \]

\[ mc = \frac{\Delta A_{ave}}{\Delta \phi_{ave}} (e_{55} + e_{55} T) + e_{66} + e_{66} T \]  
\[ (5.14) \]

where \( T \) indicates the temperature. However, the change on the temperature may not be effective on all terms. Therefore, to make the right decision while positioning the temperature dependent coefficients in equations, behavior of the constants, \( d_1, d_2, d_3, d_4, d_5 \) and \( d_6 \), are observed when pieces are subjected to the temperature changes. In addition to that as the second way of checking, first Eq. (5.12), Eq. (5.13) and Eq. (5.14) are used without any change, and then predicted coefficients are reviewed. Some of the coefficients are extremely small which means they do not have effect. Coefficients \( e_{4T} \) and \( e_{6T} \) are removed since they do not have any influence on the calculations for any of the Eq. (5.12), Eq. (5.13) and Eq. (5.14). New forms of equations are given as;

\[ \rho_w = \Delta A_{ave} (e_{11} + e_{12} T) + \Delta \phi_{ave} e_{22} \]  
\[ (5.15) \]

\[ \rho_d = \Delta A_{ave} (e_{33} + e_{33} T) + \Delta \phi_{ave} e_{44} \]  
\[ (5.16) \]

\[ mc = \frac{\Delta A_{ave}}{\Delta \phi_{ave}} (e_{55} + e_{55} T) + e_{66} + e_{66} T \]  
\[ (5.17) \]
The measured data obtained from three temperature ranges are combined for use in the further analysis steps. Now, there is just one set of data having wide range of temperatures for each wood piece group. By applying the same procedure as described above, coefficients are calculated as shown in Table 5.14.

![Hemlock pieces, moisture content %](image)

Figure 5-27: Hemlock pieces, moisture content %
Chapter 5. Measurements and Results

Figure 5-28: Small Douglas fir pieces, moisture content %

Figure 5-29: Big Douglas fir pieces, moisture content %
Figure 5-30: Hemlock pieces, wet density [kg/m$^3$]

Figure 5-31: Small Douglas fir pieces, wet density [kg/m$^3$]
Figure 5-32: Big Douglas fir pieces, wet density [kg/m$^3$]

Figure 5-33: Hemlock pieces, dry density [kg/m$^3$]
Figure 5-34: Small Douglas fir pieces, dry density [kg/m³]

Figure 5-35: Big Douglas fir pieces, dry density [kg/m³]
Chapter 5. Measurements and Results

From Figures 5.28 to Figure 5.36 show all three estimations for three wood groups.

**Table 5-15:** Standard errors of estimated wood physical properties

<table>
<thead>
<tr>
<th>Std. errors</th>
<th>hemlock</th>
<th>small Douglas fir</th>
<th>big Douglas fir</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture content</td>
<td>1.02</td>
<td>2.27</td>
<td>2.30</td>
</tr>
<tr>
<td>wet density</td>
<td>3.8</td>
<td>9.7</td>
<td>9.4</td>
</tr>
<tr>
<td>dry density</td>
<td>16.7</td>
<td>93.2</td>
<td>40.7</td>
</tr>
</tbody>
</table>

Moisture content standard error is calculated in percentage while wet and dry standard errors have units of kg/m³. For any physical property prediction, hemlock pieces give better results than the small and big Douglas fir pieces.

To summarize, grain angle, wet density, dry density and moisture content prediction formulations are introduced in this chapter. The grain angle estimation results in low standard error values and almost linear graphs, as desired. The other three physical properties are somehow related and affecting each other. The first calculated property of these three is the wet density. By using the formulation constructed the wet density of wood is predicted very successfully from the measured data. Its prediction gives very low standard errors and very compact graphs with high correlation coefficient values. On the other hand, the same success cannot be obtained for the dry density estimations of wood. During the analysis of the data, an unexpected behavior is observed for the dry density predictions. The actual-predicted dry density graphs deviate after a value where they were supposed to be going linear. When the wood pieces responsible for this behavior were checked, it is found that they were all almost the same pieces coming from the same place. Therefore, this undesired and unexpected behavior may be due to the structure of the wood pieces.
Chapter 6
Conclusions

In this thesis, a microwave system is demonstrated that can be used to estimate wood grain angle, moisture content and specific gravity. Measurement of these three wood properties is important for process and quality control in wood products manufacturing. The attractiveness of the microwave system is that it can indicate all three properties largely independently of each other. Most other types of sensors do not have this capability. For example, the RF sensors commonly used to indicate moisture content are also strongly influenced by specific gravity and grain direction variations. The greater capability of the microwave method is largely due to the much richer set of measured data. Rather than the one or two measurements typically available with other sensors, the microwave method provides up to eight separate data at each measured point. These data provide good opportunities for reliable estimation of wood physical properties.

The measurement arrangement described here builds on a 50 year history of using microwaves for identifying wood properties. Earlier systems used a single measurement of attenuation to identify wood moisture content, and subsequent designs making perpendicularly polarized attenuation measurements and also phase measurements. This work brings these ideas together into an organized set of "complex attenuation" measurements, i.e., identification of the real and imaginary attenuation components for perpendicular polarizations. This approach allows identification of the principal complex attenuations, i.e., the attenuations parallel and perpendicular to the wood grain. The principal
Chapter 6. Conclusions

Attenuations are important because they relate directly to material properties, and they exclude any influence of local wood grain direction. This is an important feature in keeping the property estimates independent of each other.

Another feature of the present work is that it explicitly accounts for the effects of temperature changes. Again, temperature sensitivity research has a long history, but it has mostly been confined to descriptive studies. The explicit use of temperature as an additional estimation variable, as is done here, seems rare.

The most common style of electrical system used for microwave measurements uses a microwave transmitter and receiver pair for each measurement. This is a costly arrangement because microwave components are expensive compared with conventional electrical components. Multiple channel systems can easily become economically unattractive. Again, this thesis research builds on previous developments, in particular the work of King. King's homodyne system using dipole scatterers is extended to multiple polarizations, and the extraction of the complex attenuations is simplified by using audio frequency modulation instead of using RF as an intermediate frequency. The main advantages of using dipole scatterers is that they are small (2cm diameter) and therefore make very localized measurements. In addition, several of them can be used within the microwave field within a single transmitter/receiver pair, without involving the need for any additional microwave components. The audio frequency modulation technique used here greatly simplifies the future use of multiple dipoles.
The microwave measurement system described here was tested using sets of wood samples of different species, hemlock and Douglas fir, all of them tested within three different temperature ranges from 0 to 28 °C. In general, the results with hemlock were the most attractive. For the two species, the standard errors of estimation (SEE) were respectively: for moisture density, 4 and 10 kg/m³, for dry wood density, 40 and 65 kg/m³, for moisture content, 1.0 and 2.0 %, and for grain angle 0.9 and 2.5 degrees. The moisture content standard error is similar to that found with conventional capacitance-type moisture meters. However, they are not able to identify grain angle or dry wood density. The reason for the species dependence with microwave measurements is not clearly known; it is also an issue with capacitance-type moisture meters. Variations in extractive and salt content seem likely candidates.

The above results confirm the promising character of microwave technology for wood property estimation. Further tests with larger batches of wood samples are needed to investigate the species dependence observed here and to identify the reasons for scatter in the estimations. Some electrical challenges also remain, particularly relating to microwave reflections and diffraction. In this study, these artifacts were controlled by the strategic use of microwave-absorbing foams. In future work, it is suggested that more specialized design principles be sought that could minimize the reflection and diffraction artifacts more robustly. That would render the microwave system a truly practical device and further improve the wood property estimation capabilities. It is the lack of robustness that is the likely reason for the slow implementation of previous microwave technology in the wood
industry. The microwave system described here is practical and effective, and is an excellent candidate for industrial implementation.
## Nomenclature

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Magnetic field (phasor)</td>
<td>Wb m(^{-1})</td>
</tr>
<tr>
<td>( \overline{B} )</td>
<td>Magnetic field</td>
<td>Wb m(^{-1})</td>
</tr>
<tr>
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<td>Electric flux density (phasor)</td>
<td>C m(^{-1})</td>
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<td>Electric field intensity (phasor)</td>
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<td>I</td>
<td>Output signal from the system in phase with reference signal</td>
<td>Volts</td>
</tr>
<tr>
<td>J</td>
<td>Current density (phasor)</td>
<td>A m(^{-2})</td>
</tr>
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Bibliography


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Bibliography


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