ACOUSTIC WAVE PROPOGATION TESTING TO DETEMINE QUALITY IN TIMBER AND TIMBER PRODUCTS

By

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Dr. Mathew Leitch	Scott Miller
Major Advisor	Second Reader

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ABSTRACT

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Key Words: Non-destructive evaluations, acoustic velocity, modulus of elasticity, modulus of rupture

Assessing and grading of raw materials in the timber industry is a key factor in the maximization of extracted value. Several different approaches are utilized to measure the quality of standing timber and sawn lumber. Assessments typically involve physical measurements, but have evolved to include non-destructive evaluations, machine strength rating and acoustic wave-length assessments to predict the strength potential and overall value of timber more accurately.

This report explores acoustic testing methods to determine qualities associated with standing and raw timber properties, such as strength, hardness, and density, which ultimately impact the value of wood products and how wood mills efficiently utilize and market their wood products. Results gathered in acoustic studies are conflicting when presenting correlations between wave propagation and density, but most agree that targeting specific species in proper temperatures generates consistent results. Acoustic testing is less effective on standing timber when compared to whole log timber where two faces are present for testing. Applications of acoustic technologies at all stages of the wood supply chain could considerably increase the utilization of forests products. These applications include the use of handheld technologies used by technicians and technologists, processing heads in harvesting operations and on mill sites before the sawing process begins.

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ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Assessment of raw wood quality is an important consideration in the processing of wood materials, and as the forest products industry is continually under economic stress to utilize natural resources while reducing waste, emphasis is being placed on new technologies to use wood products with more efficiency (Dyck 2002; Wang and Carter 2015; Xu and Walker 2004). The use of acoustic waves of different varieties has become a tried-and-true method of non-destructive testing in wood products (Amateis and Burkart 2015; Baar et al. 2011). Wave propagation in wood, coupled with density and the modulus of elasticity, (MOE) is the foundation of determining elastic, dampening and strength properties in raw wood materials (Wang and Carter 2015). Conventionally, physical characteristics (heights, diameter at breast height (DBH), taper and sweep) have been the method to determining the quality of standing or sawn timber, but do not give insight on the reliability of stiffness or strength (Amateis and Burkart 2015; Wang and Carter 2015). As such, a variety of non-destructive evaluations have become common throughout different stages of forest management and wood processing to evaluate the effectiveness of a products end use and ensuring quality assurance while perpetrating minimal damage to the product in question (Krajnc et al. 2019; Krause et al. 2014).

1.1. Objective

The main objective of this report is to research and present current literature on the use of acoustic wave propagation in standing timber, sawn logs and wood products by the forest industry for the purpose of maximizing profit. This report covers the importance of the timber industry in Canada, basic tree development, measures of strength and quality in wood using typical wood testing methods (MOE, MOR, density) and the increasing use of acoustic testing as a non-destructive evaluation.

2.0 LITERATURE REVIEW

2.1.Overview of Canada’s Forest Sector

The forest sector in Canada performs an important role in the nations economy, proving itself to be a sustainable livelihood for communities across the country. About 205,000 people work in the Canadian forest sector, 12,000 of that number being Indigenous people of Canada (Government of Canada 2020a). The nation boasts over 347 million hectares of forested land that accounts for roughly 35% of the country’s total land area, about 9% of the forests worldwide (Government of Canada 2018a). Over three-quarters of Canada’s forest is present in the nation’s boreal region, where coniferous forests account for 68% of Canada’s total forest area and contribute a significant number of the pulp ($9.7 billion), paper ($10.4 billion) and wood ($18.5 billion) that is exported every year (Forest Products Association of Canada 2021; Government of Canada 2018a). The remainder of Canada’s forest types are mixedwood (16%), broadleaf (11%) and non-treed (6%) species (Government of Canada 2018b). The annual gross domestic product for the forest sector in Canada is roughly $22 billion (Forest Products Association of Canada 2021; Government of Canada 2018a). A large part of Canada’s success in the forest sector is its ability to adapt and utilize wood and its by products, such as waste created during logging operations and in the nation’s sawmills. Canada has attempted to capitalize on this forest waste for years by converting harvest debris and sawmill waste into energy, while striking a balance in debris retention on harvest sites to ensure nutrient availability remains on the ground and habitats are provided through elements like coarse woody debris (Roach and Berch 2014). Research in Canadian forests and tree growth properties continue to be relevant to harness forest resources in a sustainable and economic fashion.

2.2.Canada's Forest Distribution and Landscape

Canada's boreal region covers about 5.5 million km^2 and stretches across the nation coast to coast, encompassing parts of ten ecozones (Government of Canada 2018b). The ecozones in which the boreal forest sits include the Pacific Maritime, Boreal Cordillera, Taiga Cordillera, Montane Cordillera, Taiga Plains, Boreal Plains, Taiga Shield, Boreal Shield, Hudson Plains, and the Atlantic Maritime ecozones (Government of Canada 2018b). The Canadian Boreal forest is shaped by the naturally occurring disturbances that have been present in the region for centuries (Government of Canada 2020b). These disturbances include wildfires and insect outbreaks, both of which have been studied extensively and continue to influence how Canadian forest management policies evolve (Government of Canada 2020b).

2.3.Tree Development

Tree growth occurs when leaves absorb carbon dioxide from the air, light energy converted from the sun and water from the soil (Wilson 1984). This combination of processes is known as photosynthesis, a function by the tree to produce carbohydrates, which are the basic molecular components that result in tree growth (Wilson 1984). Tree roots take up nitrogen and minerals from the soil, which work in conjunction with the carbohydrates from the photosynthesis process to create a variety of substances used by the tree in its growth (Wilson 1984). The stems and branches of a tree work to transport water, minerals, and nitrogen around the tree (Wilson 1984). Tree growth is an intricate process and is regulated mainly by growth regulators (promoters and inhibitors) which dictate cell growth in all areas of the plant body (Wilson 1984). Plant growth regulators control the growth that happens by the tree when exposed to the uptake, production, and transport of the basic tree growth materials, such as carbon dioxide and light energy to produce photosynthate, and oxygen, and water (Panshin and De Zeeuw 1980; Wilson 1984). Many factors come into play when in the development of individual cells, including internal and external factors like temperature, physical stress, and water stress (Wilson 1984).

Trees grow height growth and diameter (Shmulsky and Jones 2019; Wilson 1984). Height growth is a result of cell division in apical meristems found in the stems, branches and roots of trees, resulting in the upward (additive) or outward (multiplicative) movement of the terminal bud (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019; Wilson 1984). Diameter growth occurs in the vascular cambium, which is a lateral meristem comprised of a tangential band of cambial initial cells located between the xylem and phloem layers of the tree (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019).

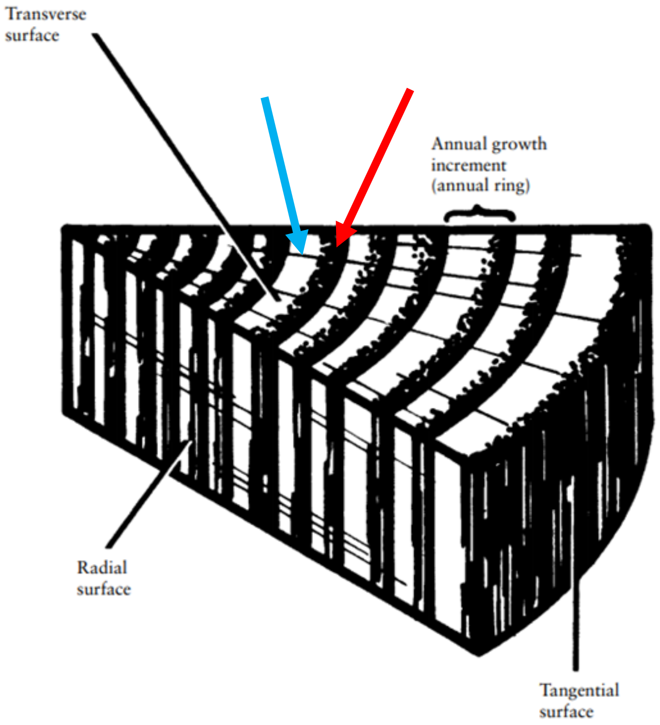
2.3.1. Wood Formation

Cambial cells of the tree thicken the stem of the tree because of the structure set in place by division, elongation, and maturation of cells from the cambium (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019; Wilson 1984). Most of a tree’s bulk is a result of cambial activity on the xylem side of the cambium (Panshin and De Zeeuw 1980). The cambium acts as a continuous sheath under the bark, on all roots, stems and branches. The activity of the cambium on the xylem side produces what is seen on a cross section of the tree as annual growth rings (Panshin and De Zeeuw 1980; Wilson 1984). Longitudinal oriented cells from the cambium grow in diameter and length and develop a secondary wall, which hardens as lignin is deposited (Shmulsky and Jones 2019). Radially oriented cells from the cambium develop rays that allow radial transportation to the cambium and phloem from the active sapwood region (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). The secondary cell wall has three distinct layers, known as the S1, S2 and S3 layers (Shmulsky and Jones 2019). The S2 layer of the cell wall is much thicker than the S1 and S3 layers (Shmulsky and Jones 2019). These layers are nearly aligned when trees produce juvenile wood, which allows flexibility in the stem. As a tree ages and increases in size, the S2 layer shifts to nearly a 90-degree angle to the S1 and S3 layers, resulting in increased stiffness of the stem (Panshin and De Zeeuw 1980; Forest Products Laboratory 2010). This development is important to consider in the behavior of wood (Shmulsky and Jones 2019).

2.3.2. Growth Rings

Annual growth rings are formed, as a rule, in temperate localities as distinct layers of growth in a woody stem with favourable temperatures occurring in the spring accelerating growth, slowing in the summer and ending in the fall (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). This results in a dormancy period that creates annual growth rings. In more climatically stable regions, such as the tropics, trees may grow all year long, making the common ring counting method to determine a trees age unreliable (Shmulsky and Jones 2019). Growth rings in temperate regions consist of earlywood and latewood tissue, with latewood typically being denser, forming the visibly darker portion of the ring, seen in figure 1 (Panshin and De Zeeuw 1980;

Shmulsky and Jones 2019). This varies from species to species however and is not considered a general rule. Early and latewood formations are found to have varying mechanical properties throughout a stem, even when in proximity in a single growth ring, but latewood is recognized as possessing two to three times the strength and stiffness of earlywood (Shmulsky and Jones 2019).

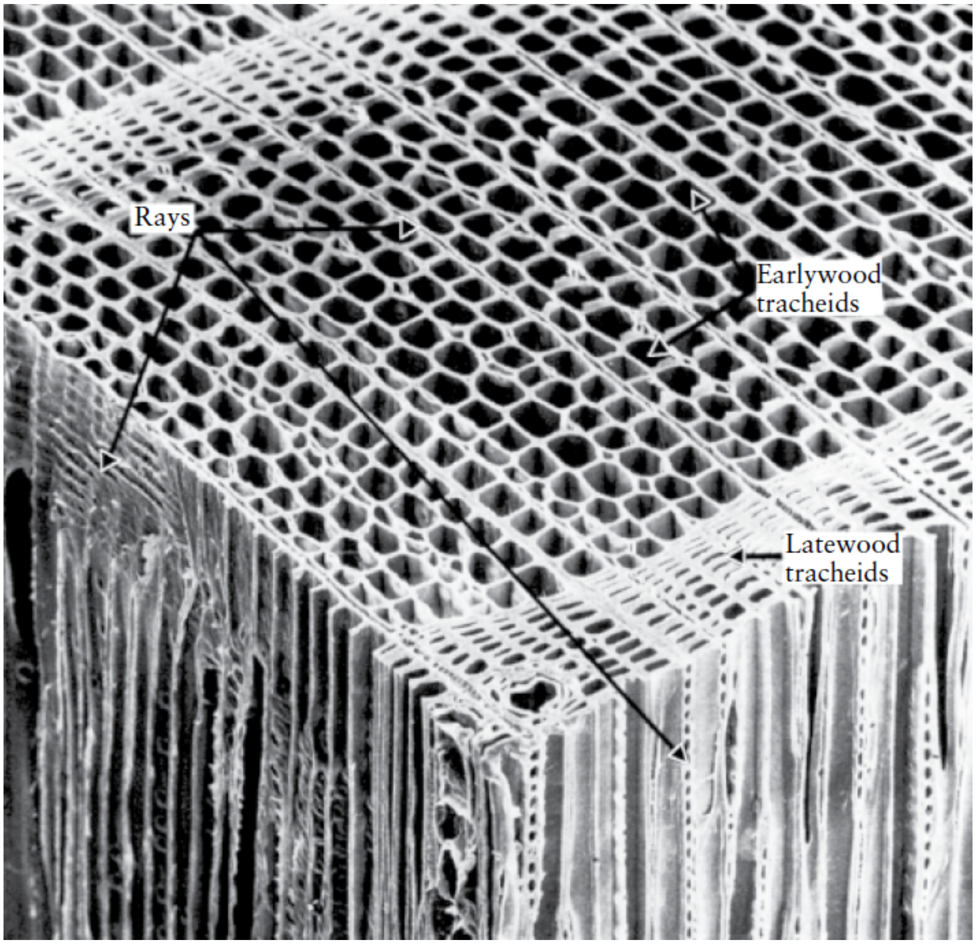


(Shmulsky and Jones 2019)

Figure 1. Three main surfaces of wood, indicating the placement of typical annual growth rings. The red arrow indicates the latewood, and the blue arrow indicates the early wood.

2.3.3. Softwood Anatomy

Wood tissue forms in the basic division of apical meristem cells, resulting in longitudinal growth in the stems, roots, and branches, while radial/girth growth occurs in the vascular cambium (Ilvessalo-Pfäffli 1995; Panshin and De Zeeuw 1980). The cambial initial, found between the xylem and the phloem of a stem, is typically one cell wide in dormancy and divides in the early stages of the growing season, creating new wood on the inner side and new phloem cells on the outer side (Ilvessalo-Pfäffli 1995; Panshin and De Zeeuw 1980). Softwood cell structures in general, are simpler and more homogenous than hardwood cell structures, consisting of longitudinal tracheids, longitudinal and horizontal resin canals and radial rays (Butterfield and Meylan 1980; Forest Products Laboratory 2010; Zobel and Buijtenen 1989). Longitudinal tracheids are vertically elongated cells that are primarily conductive and supportive, range from 2mm to 7mm in length, and make up over 90% of the wood volume in softwood (Hoadley 1990; Shmulsky and Jones 2019). Resin canals are tube like ducts in certain softwood species in which the epithelial cells secrete resin and can be longitudinal or horizontal (Hoadley 1990). Rays are flattened bands of parenchyma cells arranged radially in the stem of a tree (Forest Products Laboratory 2010; Hoadley 1990). An electron micrograph scan of softwood structure is presented below in figure 2.



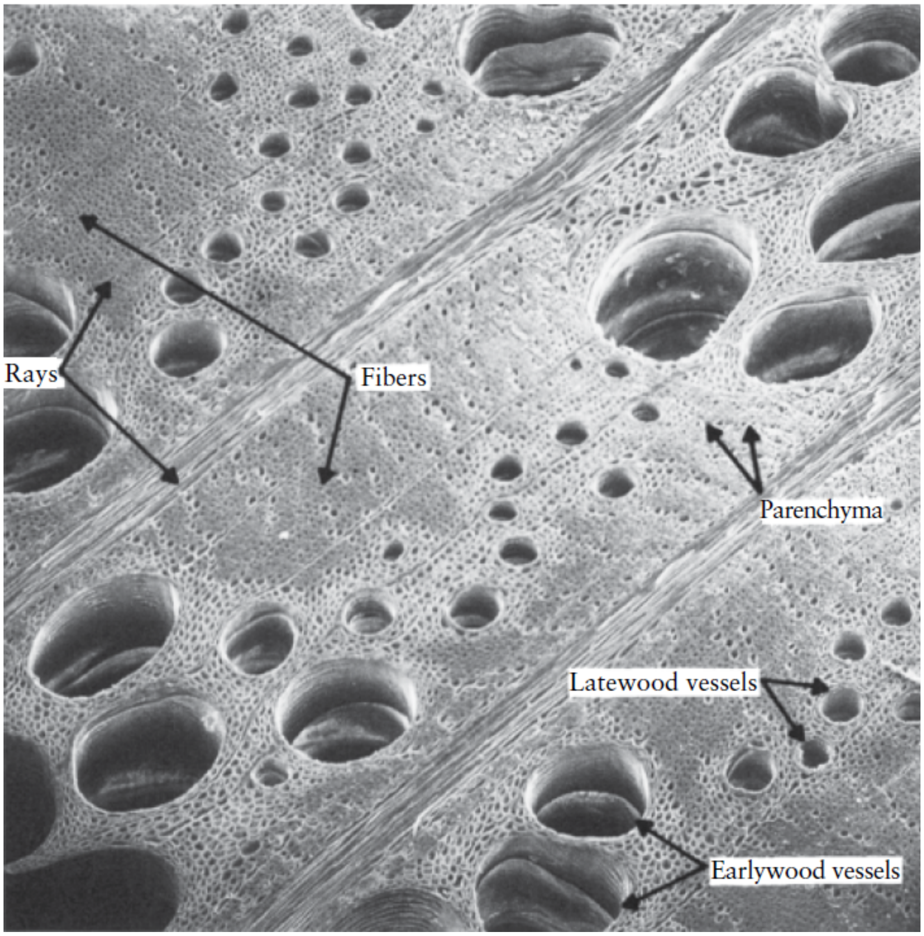
(Shmulsky and Jones 2019)

Figure 2. The main cell types found in a softwood species.

2.3.4. Hardwood Anatomy

Hardwood cell composition is more complex than softwood cell composition and possess less consistency between different species (Forest Products Laboratory 2010; Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). Hardwood cells are not normally aligned in straight radial rows, as found in softwood cells (Shmulsky and Jones 2019). Hardwood species are made up of four major cell types, and the quantity of these individual cell types can vary from species to species (Forest Products Laboratory 2010;

Shumlsky and Jones 2019). The main hardwood cell types are fibers, vessel elements, longitudinal parenchyma, and ray parenchyma (Forest Products Laboratory 2010; Shmulsky and Jones 2019). The fibers found in hardwood species are shorter than those found in softwood species, comprising a length of less than 1mm as an average (Shmulsky and Jones 2019). Unlike softwood species, hardwoods include vessels, which are made up of vessel elements (Forest Products Laboratory 2010; Schulmsky and Jones 2019). An electron micrograph scan of hardwood structure is presented below in figure 3.



(Shmulsky and Jones 2019)

Figure 3. The main cell types found in a hardwood species. Note that this image is Oak, which displays the vasicentric tracheids around the earlywood vessels.

2.3.5. Genetics

Improvement of wood quality and lumber yield is a direct result of tree genetics, and environmental conditions in which the tree finds itself (Forest Products Laboratory 2010; Panshin and De Zeeuw 1980; Shmulsky and Jones 2019; West 2006). Genetics control the individual traits of a tree (vessels that are in radial multiples versus clusters, for example), while the environment in which a tree finds itself dictates the successful production of those traits (Frankham et al. 2009; West 2006). Moisture availability, soil type, climate and elevation are examples of environmental factors that will dictate the success of tree growth (Forest Products Laboratory 2010; Frankham et al. 2009; Panshin and De Zeeuw 1980). Significant effort has been placed in the crossbreeding of high-quality seed progeny with the goal of combining the best features of superior species (Shmulsky and Jones 2019; West 2006). One sought-after quality in these cross breeding's is wood quality characteristics to develop fast growing trees that yield wood that displays average or higher than average density (Shmulsky and Jones 2019; West 2006). A term used in the field to express the potential for the transfer of genetics is heritability, usually stated as a number from 0 to 1, signifying the degree to which variation is established by the parent trees (Frankham et al. 2009; Shmulsky and Jones 2019). Using this expression, a heritability of 0 indicates that the environment was the catalyst in determining the characteristics of a tree; the closer to the value of 1 indicates how much parental influence is present in the characteristics of a tree (Frankham et al. 2009; Shmulsky and Jones 2019).

2.3.6. Site Regime

Site regime and indicators of sites, like soil moisture regime, contribute a considerable role in the tree growth process, with direct links being made between lumber quality and site variables, including forest type and productivity (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019; Sims et al. 1996). Soil moisture regime is also an important influence in tree growth, stand composition, competition, nutrient availability, and overall site quality (Sims et al. 1996). For example, Sims et al. (1996) found that site quality of naturally occurring black spruce was highly related to soil moisture and nutrient availability and that other species across northwestern Ontario preferred varied ranges of soil moisture regimes. Considerations of site quality and soil moisture regime and genetics can help better understand the ecology and quality development of targeted species (Shmulsky and Jones 2019; Sims et al. 1996).

2.4.Defects

A defect is identified in a wood stem when any irregularity or abnormality is present that will lower the strength, grade value or quality of the materials processed from that stem (Hoadley 1990).

2.4.1. Knots

In consideration of sawlog and veneer quality, knot frequency can be the most important factor in lumber grading, and therefor overall value (Shmulsky and Jones 2019). As new growth increases the amount of wood material added to the main stem of a tree, previously grown branches and their bases become locked deeper into the trunk as they become enveloped by the newly formed wood (Hoadley 1990; Shmulsky and Jones 2019). The encasing that develops around a knot is typically the result of a branch dying, along with its cambial layer, and being grown over by the main bole as it continues its normal cambium growth and could eventually lead to a loose or encased knot that risks separating and falling away from the processed wood after drying (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). These are known as dead knots (Hoadley 1990). A live knot occurs when the branch that creates the knot is alive at the time of its integration into the wood and causes a less significant defect when sawn (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019).

All trees create knots from the branches; however, several methods can be introduced in the silvicultural tree planting stages and thinning stages of the tree's development to mitigate the frequency or intensity of knots (Shmulsky and Jones 2019). Spacing at the time of planting, time of planting, execution of thinning, growth acceleration treatments and pruning can all reduce the frequency of knots in wood (Shmulsky and Jones 2019). An example of knots in lumber is presented in figure 4.

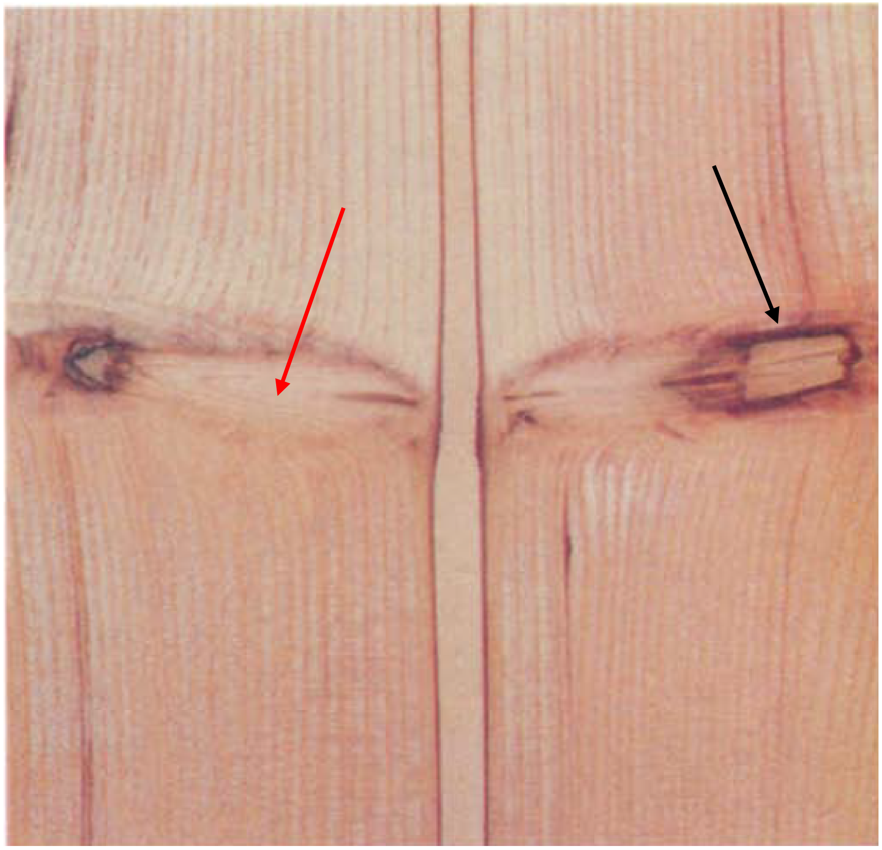
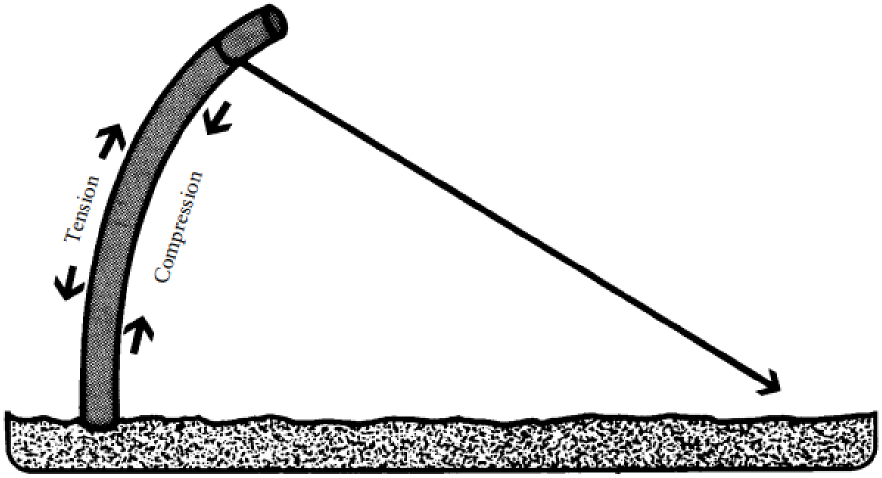


Figure 4. Example of knots in lumber, which affect lumber grade. The red arrow indicates the live portion of a knot, the black arrow indicates the dead portion of a knot.

2.4.2. Reaction Wood

Reaction wood occurs naturally in young trees as they move in the wind and are exposed to snow pressure (Krause et al. 2013). This usually causes the formation of reaction wood in the base of the tree near the pith (Forest Products Laboratory 2010; Krause et al. 2013) Reaction wood can be produced as an abnormal occurrence in response to a triggering event in which a stem is tipped from its vertical axis, becoming nonparallel to the pull of gravity (Hoadley 1990; Krause et al. 2013; Shmulsky and Jones 2019). Reaction wood formation is a functional mechanism for the redirection of a stems growth to become once again vertical, which causes the live stem to bow and in turn creates lumber with visible sweeps (Hoadley 1990). The cell walls of wood are formed by microfibrils that act as the framework to where lignin is deposited (Wilson 1984). As the lignin is deposited, it typically swells and pushes the microfibrils apart equally. In reaction wood, the upper side of the microfibril angle is at its smallest, causing tensile stress, while the sides remain nearly unchanged, and the under-side angle is greater and causes even less stress (Wilson 1984). In softwoods, reaction wood is typically found on the underside of the leaning stem, show in figure 5, where the pull of gravity results in compression of the stem, thus reaction wood in softwoods is known as compression wood (Forest Products Laboratory 2010; Hoadley 1990; Shmulsky and Jones 2019; Wilson 1984). A general concern in compression wood is the longitudinal shrinkage (up to 10x that of normal wood) and excessive warping defects that appears when the lumber is subject to drying (Krause et al. 2013; Shmulsky and Jones 2019). The density of compression wood is higher than in normal lumber yet does not increase the strength value of the wood, but rather decreases its value as its strength to weight ratio is decreased (Krause et al. 2013; Shmulsky and Jones 2019). In hardwoods, reaction wood is formed on the upper side of leaning stems and is known as tension wood (Forest Products Laboratory 2010; Hoadley 1990; Shmulsky and Jones 2019; Wilson 1984). Tension wood can be undesirable as it requires particular attention in pulping processes, and high amounts of tension wood in pulp leads to weaker paper products and lower pulp yields (Krause et al. 2013; Shmulsky and Jones 2019). Once treated, tension wood holds a higher cellulose content than normal wood, which can improve pulp yields under certain circumstances (Shmulsky and Jones 2019). Reaction wood is undesirable for many reasons, including creation of sweeps and crooks in milled wood and the above-mentioned increase in density and weight without the added benefit of extra strength (Krause et al. 2013; Shmulsky and Jones 2019). More important to wood properties, particularly strength, is the brittle nature that reaction wood possesses, causing it to be susceptible to abrupt brash breaks (Hoadley 1990).



(Shmulsky and Jones 2019)

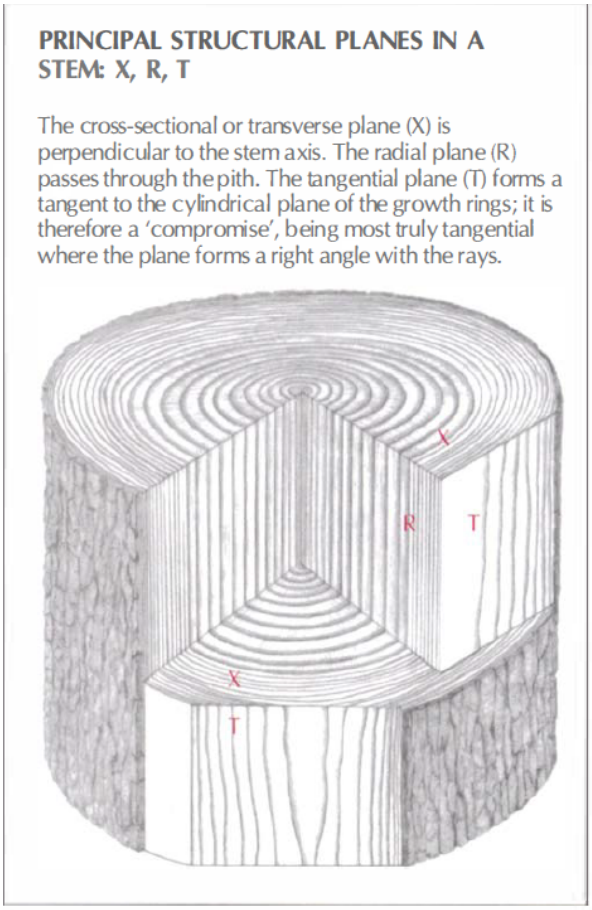
Figure 5. Demonstration of tension and compression wood in a leaning stem. Note that while this image displays both types of reaction wood on a single stem, this is for demonstration purposes only, as softwoods only possess compression wood and hardwoods only possess tension wood.

2.4.3. Sweeps and Crooks

Sweeps and crooks are the result of stems with reaction wood being milled into boards (Hoadley 1990). Compression wood, when dried, leads to longitudinal shrinkage of up to 6-7%, about 4-5% more than typical longitudinal shrinkage of 1-2% that one can expect from non-reactive milled lumber (Forest Products Laboratory 2010; Shmulsky and Jones 2019).

2.5.Attributes of Wood

Wood is formed in many plants around the world, yet not all plants that form wood meet the standard of tree classification, which is a woody plant capable of growth up to and exceeding 5 meters and comprised of a single stem (Hoadley 1990; Shmulsky and Jones 2019; Wilson 1984). Wood possesses common properties from species to species, regardless of origin (Panshin and De Zeeuw 1980). This includes being predominantly vertical, possessing radial symmetry, being cellular in structure and hygroscopic in nature (loss and gain of moisture) (Panshin and De Zeeuw 1980). Wood often has large and obvious anatomical features in which identification is made simple, but in some cases, studying a wood sample on a specific plane will expose many important identifiable features (Hoadley 1990). The three main structural planes in wood are the cross sectional (transverse), radial and tangential planes, demonstrated in figure 1 (above) and figure 6 (below).



PRINCIPAL STRUCTURAL PLANES IN A STEM: X, R, T

The cross-sectional or transverse plane (X) is perpendicular to the stem axis. The radial plane (R) passes through the pith. The tangential plane (T) forms a tangent to the cylindrical plane of the growth rings; it is therefore a 'compromise', being most truly tangential where the plane forms a right angle with the rays.

(Hoadley 1990)

Figure 6. Principle structural planes in a stem

2.5.1. Mechanical Properties

The strength and resistance of wood to deformation is described as its mechanical properties and are usually the most important characteristics of wood products for structural use (Forest Products Laboratory 2010; Shmulsky and Jones 2019). Strength refers specifically to a species ability to carry weighted loads and stiffness refers to a measure of the material that is compressed, stretched, or bent by a weighted load (Forest Products Laboratory 2010; Shmulsky and Jones 2019).

2.5.2. Moisture

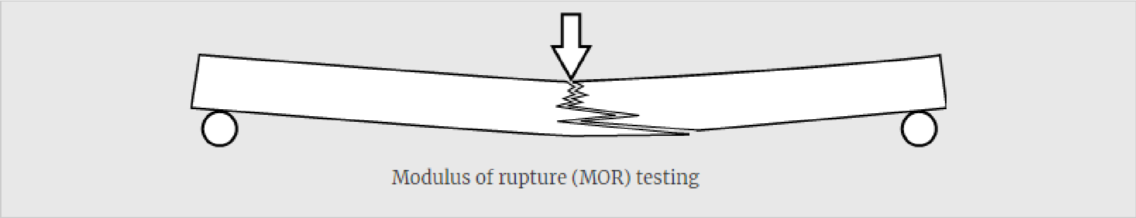
Wood is a porous material that enables absorption and desorption of water from the air, storing it in the cell membrane and cell cavities, altering the moisture content of wood (Dietsch et al. 2014). Wood reacts this way based on temperature and relative humidity in the atmosphere, referred to as equilibrium content (Forest Products Laboratory 2010; Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). Moisture content in wood is expressed as a percentage of the wood weight, with density decreasing as the moisture percentage also decreases (Forest Products Laboratory 2010; Shmulsky and Jones 2019). Changes in moisture content leads to the change of almost all physical and mechanical properties in wood products (Dietsch et al. 2014). Moisture intake and loss in wood changes dimensionally differently across the three different planes demonstrated in figure 2 and figure 4, with more pronounced swelling occurring in the radial and tangential sections (Dietsch et al. 2014). A general ratio for wood shrinkage is 1:50:100 for longitudinal:radial:tangential (Forest Products Laboratory 2010).

2.5.3. Modulus of Rupture and Elasticity

Modulus of Rupture (MOR) is often associated with a wood species bending capabilities before rupture and is an accepted representation of wood strength (Forest Products Laboratory 2010; Meier 2015). MOR is a representation of the maximum load carrying or bending capabilities of wood through the application of stress until failure (Forest Products Laboratory 2010; Shmulsky and Jones 2019). MOR is determined from the maximum load in a bending test, using the static bend testing method for determining Modulus of Elasticity (Forest Products Laboratory 2010; Shmulsky and Jones 2019). MOR is determined using the flexure formula: Bending strength = *MC/I*

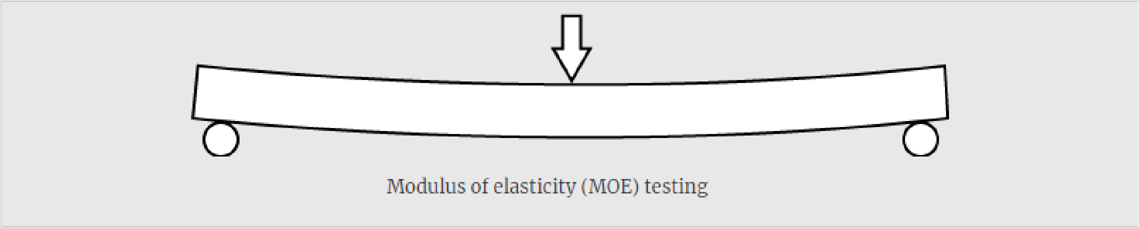
Where *M* is the maximum bend, *c* is the distance from the neutral axis to the extreme fiber, and *I* is the moment of inertia (Shmulsky and Jones 2019). In metric units, MOR can be represented as kilograms per cm^2 , or as Megapascal pressure units (MPa).

Modulus of Elasticity (MOE) is associated with a wood species stiffness and a good indicator of strength (Meier 2015). Elasticity in wood implies that the bend produced by introduced stress below the proportional limit is recoverable after the stress is removed (Forest Products Laboratory 2010). When stress is applied above the proportional limit, failure in the wood occurs (Forest Products Laboratory 2010). MOE is an important determination in wood strength properties as it determines the amount of pressure wood can deflect before failure and gives insight into how much load a final wood product can take (Forest Products Laboratory 2010; Shmulsky and Jones 2019). In metric units, MOE can be represented as kilograms per cm^2, or Gigapascals (GPa). MOR and MOE are demonstrated in figures 7 and 8. The properties of MOE-MOR increase linearly with specific gravity (Shmulsky and Jones 2019).



(Meier 2015)

Figure 7. Graphic demonstrating MOR testing



(Meier 2015)

Figure 8. Graphic demonstrating MOE testing

2.5.4. Density and Specific Gravity

Density is the most valuable indicator of strength properties in wood as it predicts important attributes like strength, hardness, ease of processing and nail resistance (Beaulieu and Dutilleul 2019; Hoadley 2000). Density can vary greatly among species due to several factors, such as locality of a tree within a stand, site condition, overall geographic location within the range of a species, and genetics (Shmulsky and Jones 2019). Density also varies within a species and within a single tree from base to crown or pith to bark (Forest Products Laboratory 2010; Shumlsky and Jones 2019). With these factors in mind, the end user of a piece of lumber does not normally have knowledge of a stem's origin or maturity level and must understand the importance of density measurements and expect variability from sample to sample (Shmulsky and Jones 2019). Wood density is expressed as weight per unit of volume (grams per cubic centimeter) and is closely correlated with the specific gravity of wood and as such, the two terms are used interchangeably though they each have their own specific definitions (Hoadley 1990; Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). Specific gravity is known as relative density or the density index, calculated as the ratio of the density of the subject substance; water in the case of wood testing (Hoadley 2000;

Shmulsky and Jones 2019). Caution should be exercised when dealing with wood densities. Since no universal standard is in place and discrepancies can arise from moisture contents, it is important to take diligent notes and to be sure of the basis of the calculation used when working with density (Shmulsky and Jones 2019). Internationally, all wood properties are reported at 12% moisture content to allow comparisons between species. Similarly, all physical and mechanical property testing is completed according to specific standards to ensure testing methodology is the same to allow for global comparisons, as exampled by the ASTM standards testing procedures (Forest Products Laboratory 2010; Shumlsky and Jones 2019).

2.5.5. Utilization and Commercial Importance

Wood products are utilized for countless applications, and the use of raw wood materials is only increasing. Basic uses of lumber include pulpwood, construction and structural timber, railway ties, and power and communication poles. Any manufacturer of wood products understands the necessity of material utilization, and their main goal is undoubtably efficiency in all aspects of their respective wood product processing (Shmulsky and Jones 2019). New technologies and innovations in lumber processing lead to new and unexplored products with an assortment of usefulness being developed, used for energy, and traded. Research organizations that have received backing by industry and governments within the past decade have been able to progress several “clean technology” products not typically utilized or exported by the Canadian Government; cellulose, nanocrystals, engineered fiber mats and biomaterial, to name a few (Canadian Council of Forest Ministers 2016). Many technologies exist to aid managers in the grading of softwood lumber, like x rays, lasers, digital photography, CT scanner and ultrasound, and in a commercial context, it is normal to see at least two of these technologies used so that internal and external defects can be identified (Shmulsky and Jones 2019).

2.5.6. Chemical Properties

Wood is mostly made up of carbon, hydrogen, and oxygen, in which the fundamental components of wood consist of cellulose, hemicellulose and lignin (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). Cellulose is formed within living cells from a glucose-based sugar nucleotide and makes up a significant amount of a trees structure (Shmulsky and Jones 2019). Lignin occurs between different cells and within the cell wall to act as a binding agent to hold cells together as well as giving cells rigidity (Panshin and De Zeeuw 1980; Shmulsky and Jones 2019). Table 1 profiles the difference in these factors between hardwoods and soft woods.

Table 1. Organic make up of Hardwoods and Softwoods.

Species Type	Cellulose (dry weight %)	Hemicellulose (dry weight %)	Lignin (dry weight %)
Hardwood	40-44	15-35	18-25
Softwood	40-44	20-32	25-35

(Shmulsky and Jones 2019)

2.6.Acoustics in Wood

Acoustic technologies have become accepted as a quality control and products grading tool within the past several decades, and in recent years have improved to a point where tree quality and wood properties can be predicted with accuracy (Amateis and Burkhart 2015; Baar et al. 2011; Wang and Carter 2015). Predictions can be made about the final wood products density and strength based on testing done on standing trees and sawn logs (Amateis and Burkhart 2015; Baar et al. 2011; Krajnc et al. 2019; Wang and Carter 2015). Since acoustic testing can be performed on manufactured wood products and standing trees alike, further improvements in acoustic technologies could lead to the improved management of wood quality, assessment of forest value and improvements of future timber within plantations (Amateis and Burkart 2015; Krajnc et al. 2019; Wang and Carter 2015). Information collected with the use of acoustic technologies could, in theory, also be used to sort and grade standing trees within forested harvest blocks based on wood quality characteristics and thus a greater understanding of the economic value of the stand may be extrapolated (Amateis and Burkhart 2015; Krajnc et al. 2019; Wang and Carter 2015). Similarly, sawlogs could be sorted more meticulously based on their suitability for structural applications and for an array of fiber properties of importance to pulp ands paper manufacturers (Wang and Carter 2015).

Acoustic velocity is performed through various acoustic testing tools and is measured in meters per square second $(m/s)^2$ (Krause et al. 2014; Baaar et al. 2011; Hansen 2006). Acoustic testing attempts to correlate the relationship between wood density and the velocity of wave propagation in a stem or log to determine physical strength properties, such as density and stiffness (Baar et al. 2011; Amateis and Burkart 2015; Wang and Carter 2015).

Since variations in genetics, soil conditions, stand density and other environmental factors affect wood characteristics, complications can arise in the acoustic measuring process (Amateis and Burkhart 2015; Krajnc et al 2019; Wang and Carter 2015). Complications also arise because of the velocity of sound wave propagation being affected by macro and microstructure, moisture content and anatomical direction of propagation (Baar et al. 2011; Krajnc et al. 2019). However, several different tests have found that despite these variations in tree development, acoustic testing is a suitable method to characterize wave propagation behaviours in stems (Amateis and Burkart 2015; Baar et al. 2011; Wang and Carter 2015).

Acoustic measurements in standing trees differs from acoustic measurements taken in individual stems cut to length, as with a standing tree there is no access to an end surface as present in a log (Amateis and Burkart 2015; Wang and Carter 2015). Therefore, two measurement methods have been developed: Time of Flight (TOF) for measurements on standing timber and resonance-based methods for logs (Amateis and Burkart 2015; Baar et al. 2011; Krajnc et al. 2019). Acoustic measurements in manufactured wood products may also differ from those for standing or sawn round log timber.

Non-destructive evaluations for stiffness and strength properties have grown quickly with the development of newly engineered wood products such as laminated veneer lumber, I- beams and I-joists, and mills have become increasingly interested in testing these properties in the most cost-effective manner possible (Wang and Carter 2015). This interest has led to the development of acoustic testing tools that allow for quick and repeatable measurements of wood quality to allow value assessments at early stages in the operational value chain (Amateis and Burkart 2015; Dyck 2002; Wang and Carter 2015).

2.6.1. Background

Quality of trees, stems and logs has typically been predicted by collecting simple physical measurements and visual observations (Amateis and Burkhart 2015; Dyck 2002; Wang and Carter 2015). These physical measurements include height, length, diameter, taper and sweep measurements, normally conducted with the use of basic tools like measuring tapes, clinometers and more modern tools like height lasers and range finders (Government of Ontario 2004; Wang and Carter 2015). While these basic measurements allow considerable insight into the overall health, condition and value of the tree or log, the sufficiency of visual grades for applications relating to stiffness and strength qualities are vague, since no true measure of those properties is gathered (Dyck 2002; Wang and Carter 2015).

In a study conducted on sound propagation in the heartwoods of tropical hardwoods, Baar et al. (2011) found that changes in wave velocity of wood were caused by the change in density and elastic modulus, concluding that increased density results in a decreased wave propagation speed. The increase in wood density typically led to increased stiffness of wood, however, if density increase was not accompanied by a similar stiffness increase, the wave propagation speed decreased with increasing density (Baar et al .2011). Baar et al. (2011) concluded that this is the reason studies attempting to link density to sound wave propagation often present varying conclusions. In a study using acoustic velocity testing to evaluate timber quality in large diameter trees, Krajnc et al. (2019) state that their findings suggest acoustic velocity in the longitudinal direction provides mean tree mechanical properties in small to average diameter trees, but that alternatives need to be developed in order to capture similar data on large diameter trees.

2.6.2. Fundamentals of Acoustic Wave Propagation

In all testing applications, testing via acoustic wave propagation begins with the introduction of stress in the surface of wood (Amateis and Burkart 2015; Wang and Carter 2015). This quick introduction of stress, normally by a hammer, causes a disturbance or vibration that travels through the wood in the form of a stress wave (Amateis and Burkart 2015; Wang and Carter 2015). There are three types of waves created by the impact: longitudinal waves, shear wave and surface wave (Krause et al. 2014; Wang and Carter 2015). These three waves are defined in table 2.

Table 2. Definition of the three types of stress waves

Wave Type	Definition
Longitudinal Wave	Determined by the oscillation of particles along the direction of the wave propagation such that the particle velocity is parallel to the wave velocity
Shear Wave	Motion of the particles carrying the wave is vertical to the direction of the wave propagation
Surface Wave	Wave is restricted to the surface. Particles move up and down and back and forth to form elliptical paths

(Wang and Carter 2015)

Acoustic wave propagation testing methods are based on the relationship between the tested material (*c*), the density of the material (*p*) and the modulus of elasticity (*E*) (Baar et al. 2011).

2.6.2.1. One-Dimensional Wave Equation

The relationship between the property of wood and longitudinal wave velocity can be determined by fundamental wave theory (Wang and Carter 2015). In long, slender, isotropic material, strain and inertia in traverse directions can be ignored, and longitudinal waves propagate in a plane waveform (Wang and Carter 2015). Wave velocity in the case of one-dimensional waves is assumed to be independent of Poisson’s ratio, and can be given the equation of:

$$C_0 = \sqrt{\frac{E}{\rho}}$$

where C_0 is the longitudinal wave velocity, E is the longitudinal modulus of elasticity and p is the density of the tested material (Baar et al. 2011; Wang and Carter 2015).

2.6.2.2. Three Dimensional Wave Equation

When dealing with an infinite or unbounded isotropic elastic medium, a triaxial state of stress is present in the wood (Wang and Carter 2015). The wave front of the longitudinal wave traveling through such a material is no longer a plane (Wang and Carter 2015). The wave progoation can be expressed as the following three-dimensional longitudinal wavbe formula:

$$C = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}\frac{E}{\rho}}$$

where *C* is the longitudinal wave velocity in unbounded medium and ν is Poisson's ratio of the material (Wang and Carter 2015). The wave velocity is dependent on density and two elastic parameters, which are the modulus of elasticity and Poisson's ratio (Wang and Carter 2015).

2.7.Application of Acoustics to Standing Timber and Logs

Complications arise when attempting to apply the fundamental wave equations to wood, particularly when dealing with standing timber and logs, as wood is not a homogenous or isotropic material (Amateis and Burkhart 2015; Wang and Carter 2015). Despite natural variances in wood, the one-dimensional wave equation has shown sufficient to characterize the wave propagation patterns in logs (Wang and Carter 2015). This is exampled in the high level of accuracy in MOE predictions in tested logs, and for this reason has been a successful grading and sorting measurement tool in wood processing industries (Amateis and Burkhart 2015; Wang and Carter 2015).

The approach to acoustic measurements in standing timber is vastly different from that used in logs, as there is no contact to the end surfaces as is the case the testing of sawn logs (Amateis and Burkhart 2015; Wang and Carter 2015). Thus, acoustic waves must be introduced from the side of the trunk, resulting in nonuniaxial stress in the stem and eliminating the possibility of using the one-dimensional wave equation (Wang and Carter 2015). While Poisson's ratio of green wood is not explicitly known, and it seems to change from species to species, statistical analysis indicates that Poisson's ratio does not vary with wood density, and an average value can be used for both hardwood and softwood species (Wang and Carter 2015).

2.7.1. Time of Flight versus Resonance Method in Tree and Log Measurement

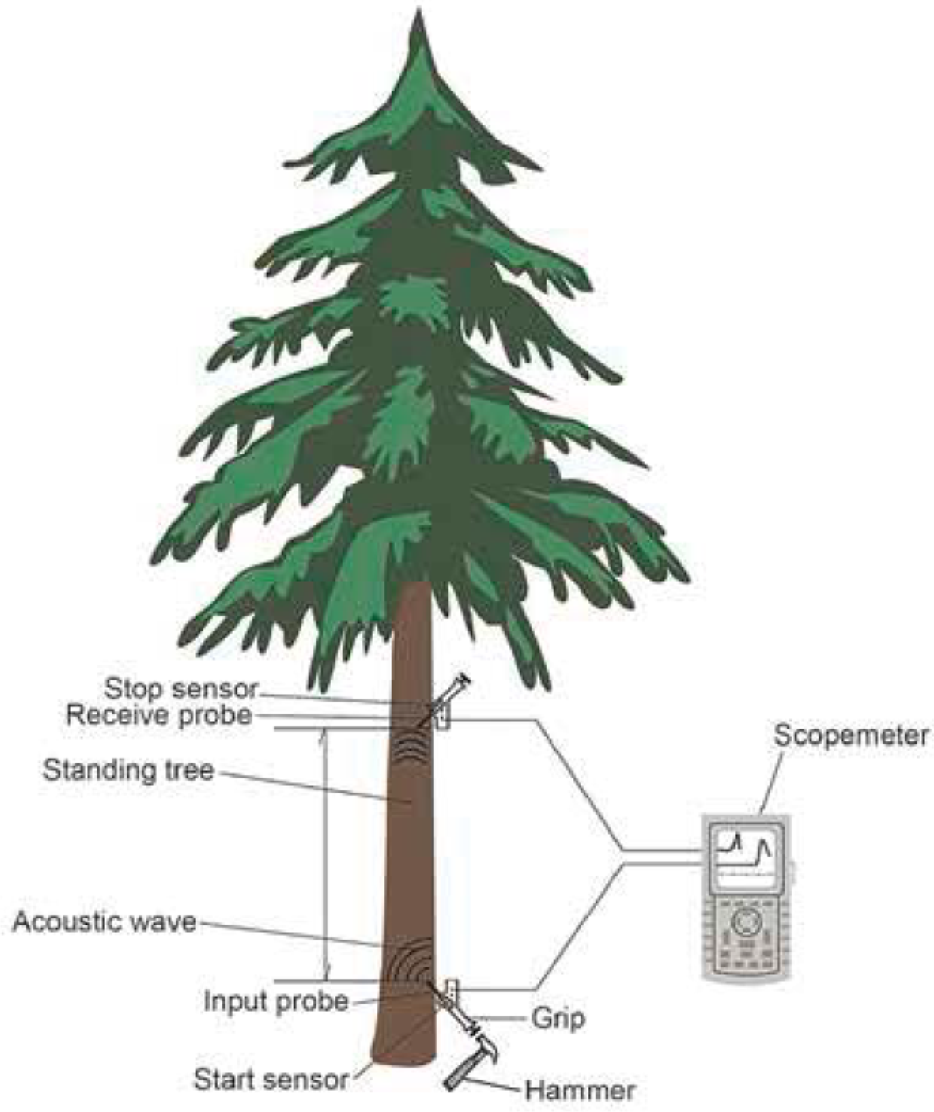
Two measurement methods have been developed for gathering acoustic wave propagation data in tree and log measurements: Time of Flight (TOF) for measurements on standing timber and resonance-based methods for logs (Amateis and Burkart 2015; Baar et al. 2011; Krajnc et al. 2019). TOF measurements are normally gathered longitudinally (parallel to the grain) on standing trees, though they can also be measured perpendicular to the grain for specific applications, such a defect detection (Krajnc et al. 2019). The acoustic velocity gathered in resonance-based methods in log testing is dependent on the weighted average wood properties and moisture content of the sample, and measures fiber properties that influence macro properties such as stiffness, strength, and stability (Wang and Carter 2015). The success of field applications to acoustic testing is related to the understanding of stress-waves in wood materials and the characteristics of wood (Wang and Carter 2015). Standing timber and sawn logs posses varying internal and external characteristics that introduce complications in the measurement of acoustic velocities (Amateis and Burkhart 2015; Wang and Carter 2015). These complications include temperatures at which testing occurs, as results of acoustic testing become inconsistent around the freezing point (Wang and Carter 2015). A change in acoustic velocity was noted by Gao et al. (2013) when investigating the impacts of temperature on acoustic wave velocities. Results from this study concluded that ambient temperatures had significant effects on acoustic velocity when temperatures fell below 0^{o}C. The change in acoustic velocity was less significant after temperatures dropped below -2.5^{o}C (Gao et al. 2013). Issues surrounding temperature effects on acoustic wave velocity can be corrected with temperature adjustments, however issues may continue to arise if measurements are taken around the freezing point (Gao et al. 2013; Wang and Carter 2015).

2.7.1.1. Time of Flight Measurement in Trees

A conventional approach for determining acoustic velocity in a stem is with the insertion of two probes, a transmit probe and a receiver probe, into the sapwood that effectively speak to one another (FAKOPP Enterprise 2021; Amateis and Burkhart 2015; Wang and Carter 2015). Time of Flight (TOF) is the measurement of time needed for a stress wave introduced by a hammer to travel from the transmit probe to the receiver probe (FAKOPP Enterprise 2021; Wang and Carter 2015). TOF methodology is typically reserved for standing timber and involves inserting both probes through the bark and cambium to reach sapwood and aligned on a vertical plane (Amateis and Burkhart 2015; Wang and Carter 2015). This methodology is presented in figure 9 below. Acoustic velocity is calculated from the distance between the two probes and the TOF using the equation:

$$C_{\mathrm{T}} = \frac{S}{\Delta t}$$

where C_T is the tree acoustic velocity in meters per second (m/s), S is the distance of the probes in meters and Δt is TOF (Wang and Carter 2015).



(Wang and Carter 2015)

Figure 9. Proper application of TOF measurements for a standing tree.

2.7.1.2. Resonance- Based Approach in Logs

Acoustic velocities in round wood of known length are measured using the resonance-based approach (Wang and Carter 2015). With this method, an acoustic sensor can be placed directly on one end of a log, where the impact can be produced, causing stress waves to be recorded by an attached electronic module (Amateis and Burkhart 2015; Wang and Carter 2015). This method observes hundreds of acoustic pulsations that resonate longitudinally in the log that delivers a weighted average of acoustic velocity (Wang and Carter 2015). The acoustic velocity gathered in resonance-based testing in log measurements is dependent on the weighted average wood properties and moisture content of the sample, and measures fiber properties like stiffness, strength and stability (Dyck 2002; Wang and Carter 2015). A challenge faced in this approach is interpreting the information gathered (Dyck 2002; Wang and Carter 2015). Acoustic velocity of a log can be determined from:

$$C_{\mathrm{L}} = 2 f_0 L$$

where C_L is acoustic velocity of the log (m/s), f_0 is fundamental natural frequency of an acoustic wave signal (Hz), and L is log length (m) (Wang and Carter 2015).

The resonance-based approach is a recognized non-destructive evaluation technique for measuring logs, poles and other round timber (Amateis and Burkhart 2015; Wang and Carter 2015). This method is a highly repeatable velocity measurement and because of its accuracy, can be used to validate the TOF measurements in standing trees (Wang and Carter 2015). An example of using the resonance-based approach of acoustic measurements is presented below in figure 10.

(Jacques 2020)

Figure 10. The transmit and receive probe of a TreeSonic acoustic measurement device set into a sample log on an acoustic testing jig, designed to reduce the loss of vibrations within the log.

2.7.2. Equipment

The TreeSonic microsecond timer is a tool designed to collect predictions of tree stiffness by measuring stress wave time between the transmit probe to the receiver probe, originally designed by Weyerhaeuser Co. (FAKOPP Enterprise 2005). This is a portable tool to be used in the manual collection of acoustic velocities by technicians in forested stands or other applications where acoustic velocities do not need to be captured quickly.

Harvesting processors with acoustic technologies built into their processing heads exist, enabling tree quality evaluations to occur during harvest (Wang and Carter 2015) This allows for the optimization of felled stems and more accurately sorted based on wood quality (Wang and Carter 2015). Acoustic technologies in processor heads measure the longitudinal TOF of a sound wave as the processing head grips a standing stem (Wang and Carter 2015). The operator can see the acoustic velocity on a display in the cab of the machine, allowing for increased cutting and sorting efficiency (Wang and Carter 2015). A study conducted by Carter et al (2013) found that processor heads with acoustic technologies were able to identify accurate stiffness measurements in logs before any mill processing had occurred, resulting in positive net benefits.

Automated on-line log sorting exists in some mills, enabling log-by-log evaluation and optimization of extracted value by offering insight into sawcut patterns to be applied (Wang and Carter 2015). An example of this technology are log graders, which are installed after the debarker at the mill site, measuring the quality of the log using acoustic measurements before being sawn (Wang and Carter 2015). Similarly to capturing data manually by using a hammer on the probes with the TreeSonic device, the technology for assessing acoustic velocity in the mill utilizes a swinging hammer at the end of the log to send stress through the stem and resonant frequency is measured via microphones (Wang and Carter 2015). Instant analysis and calculation of acoustic velocity provide values of stiffness in the log and its suitability for use as structural or non-structural products (Wang and Carter 2015). This information is relayed to the saw operator in the mill, who can in turn adjust their cut patterns to maximize extracted value of timber in each log (Wang and Carter 2015).

2.7.3. Uses

Acoustic technology measures fiber properties that impact macro properties, like stiffness, strength, and wood stability (Amateis and Burkhart 2015; Wang and Carter

2015). Standing timber or sawn logs deliver different intrinsic wood properties, even when procured from nearly identical growing conditions and age classes (Wang and Carter 2015). Therefore, the use of acoustic wave propagation in wood offers major commercial benefits through the optimization of wood resources via grading, sorting, and processing (Amateis and Burkhart 2015; Wang and Carter 2015). The use of resonance-based acoustic methods to improve log sorting is currently recognized in the forest industry and utilized by mills to varying degrees (Amateis and Burkhart 2015; Wang and Carter 2015). Operationally, acoustic technology can be applied at numerous stages, including from the assessment of forested stands, the processing of the timber on site and sorting of raw wood materials at the mill site (Krajnc et al. 2019; Wang and Carter 2015). Different tools have been developed in the forest-to-mill supply chain to fit specific applications as required by the form that the lumber takes (Krajnc et al. 2019; Wang and Carter 2015).

2.7.3.1. Sorting Logs for Lumber Quality

Studies have shown the correlations between resonant frequencies of logs, MOE and MOR (Amateis and Burkhart 2015; Baar et al. 2011; Wang and Carter 2015). This was evidenced by Ross et al. (1997), who revealed correlations between acoustic wave predicted MOE and mean lumber MOE values, opening the possibility for the technology to be used in mills. To further understand the practicality of resonance based acoustic testing, Wang and Ross (2000) conducted a mill study where examination of potential of log sorting in relation to lumber stiffness was explored. That study concluded that logs with a higher acoustic velocity contained higher proportions of high-grade lumber (Wang and Carter 2015). The logs with the highest acoustic velocity (top

30%) produced timber that was 90% stiffer than the group scoring the lowest acoustic velocity (bottom 30%) (Wang and Carter 2015; Wang and Ross 2000).

Companies utilizing this technology currently measure the velocity of acoustic waves and sort logs into velocity groups, allowing for the selection of the greatest quality logs for structural uses, while separating low grade logs for non-structural uses or other applications (Krajnc et al. 2019; Wang and Carter 2015). This is useful for the selection of veneer grade lumber, as witnessed in a study conducted by Carter and Lausberg (2003). Results indicated that logs separated based by acoustic velocity resulted in a production of 52% premium high stiffness veneer product, compared to lower grade sorts that resulted in 24% (Carter and Lausberg 2003; Wang and Carter 2015). Economic gain was also noted in the sorting of veneer logs for the purpose of LVL production, resulting in a gain of USD\$16/m^3 on log volume (Carter et al. 2005).

2.7.3.2. Assessment of Standing Trees

Like in the assessment of sawn logs, research of acoustic wave propagation in standing timber has yielded positive economic applications in the development of harvest scheduling and timber markets centered on the possibility of stress-graded products obtained from forested stands (Amateis and Burkhart 2015; Wang and Carter 2015). A study conducted by Wang et al. (2005) tested a variety of softwood species to determine a linear correlation between tree velocity and log velocity. The relationship between these values were skewed, with tree velocity being significantly higher than those of sawn logs (Wang and Carter 2015). This supported that the TOF measurement in standing timber is dominated by dilatational or quasi-dilatational waves rather than one-dimensional waves, seen in the testing of logs (Wang and Carter 2015). The deviation in velocities and skewed relationship between the standing tree measurements and sawn log measurements can be interpreted differently through multivariate regression models and adjustments can be made to make proper determinations about wood quality, effectively reducing or removing the deviations (Wang and Carter 2015).

When using acoustic velocity testing methods on standing trees, TOF measurements are normally gathered longitudinally (parallel to the grain) (Krajnc et al. 2019). Tests can be completed perpendicular to the grain in standing trees in order to detect potential defects in specific portions of a stem, and is a method occasionally used by arborists in single tree assessments (Krajnc et al. 2019). In standing trees, the mechanical properties of interest are typically the strength grade-determining properties, such as MOE, MOR and density (Krajnc et al. 2019).

With velocity measurements, forested stands can be assessed and sorted by structural qualities based on collected velocities, and in turn value for the stand can be more accurately determined (Amateis and Burkhart 2015; Wang and Carter 2015). Further, forest management decisions can be influenced by the acoustic velocity data collected, since acoustic velocities applied to standing trees is relevant to tree breeding, pre harvest assessment and decision support at the time of stand thinning (Amateis and Burkhart 2015; Wang and Carter 2015).

Several mill trials conducted by Huang (2000) showed that trees sorted by high and low stiffness were determined by tree acoustic velocity alone. Other non- destructive evaluation methods such as machine stress rating and ultrasound veneer grading have been the standard for testing wood stiffness and strength, but research has shown that these predictions can accurately be made through simple acoustic measurements in standing timber (Wang and Carter 2015).

Computed Tomography Scanning

Computed Tomography (CT) scanning technology is a valuable, non-destructive tool used for the optimization of value in raw wood through three-dimensional computed tomography (Beaulieu and Dutilleul 2019; Gergel et al. 2019). Scanning technologies in the timber industry are similar to those in medicine but are instead built to scan logs on an industrial scale (Beaulieu and Dutilleul 2019; Gergel et al. 2019). In simple terms, a CT scan works through the absorption of X-rays by the sample being scanned in the CT (Beaulieu and Dutilleul 2019). A basic scan of a log provides 3D models of specific cuts that can be made by a saw operator at the mill, as well as provide insight to the location and severity of internal defects (Gergel et al. 2019). CT measurements can measure internal wood density as the X-ray attenuation coefficient of a voxel is related to a materials density (Beaulieu and Dutilleul 2019). Since a density variation exists between early wood and latewood in temperate regions, it is possible to delineate annual growth rings using CT scan data (Beaulieu and Dutilleul 2019).

3.0 CONCLUSION

Acoustic testing is an accepted method of testing wood quality characteristics such as density and strength and can be applied to unprocessed, standing trees and logs or finished wood products like laminated veneer lumber, I- beams and I-joists. The continuing economic pressures that the forest industry faces dictate the development of technologies that increase utilization and efficiency both at the harvest site and in the mill. Applications of acoustic technologies at all stages of the wood supply chain could greatly improve the utilization of forests and their harvested products. These applications include the use of handheld technologies used by technicians and technologists, processing heads in harvesting operations and on mill sites after the debarking occurs, but before the sawing process begins.

Several studies have shown the correlation of acoustic wave propagation to density and the modulus of elasticity, proving that acoustic technologies are a reliable non-destructive evaluation of wood properties in its different forms. Conventional physical measurements such as DBH, height, taper and sweep provide insight into a stem's overall health and value but coupled with the ability to tally density predictions in the field could allow for more effective management decisions to be made. The ability to use acoustic testing as a non-destructive evaluation method at all stages of the wood processing stages ensures quality assurance while causing minimal damage to the products in question, allowing for increased utilization.

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