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Ultrasonic wave attenuation and velocity in the transverse direction were used to detect defects in ponderosa pine (*Pinus Ponderosa*) lumber previously dried from green to 9% moisture content. After ultrasonic testing the boards were visually inspected for defects and classified according to the defects present. An ANOVA with Bonferroni pairwise comparison were used to establish differences between clear and defective wood. There are differences in the parameter means between clear wood and wood containing defects; however, variability in the measured parameters is great, preventing an accurate separation of defective wood from clear wood. Because of this application in industry is limited.

Detection of Defects in Wood by Ultrasonics

by

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Ramon Gonzalez Gimenez, Author

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Dedicated to my parents, brother and sister in law and to the spirit of this great country in which I still believe.

DETECTION OF DEFECTS IN WOOD BY ULTRASONICS

1- INTRODUCTION

Defects, such as surface checks and honeycomb, produced by the drying process are not common in lumber that has been properly dried. When internal defects do occur, however, they are not detected. These defects appear later in processing or in the final product when much effort and money has been added to the product, causing large losses in secondary manufacturing industries. This project was undertaken because high quality pine lumber is often resawn or sliced into veneer. The veneers are used as overlays and defects are very visible in the final product after a finish is applied.

Some methods, such as x-rays, have been used to detect defects in wood, but their cost and lack of adaptability to production lines prevent their application in the industry. Ultrasonics may provide a solution to this problem because they are easy to use, cost effective, and can be adapted to production speeds. A nondestructive evaluation technique using ultrasonics has been tested successfully to detect knots and bacterial infection in oak (Ross et al, 1992). The technique uses mainly two sound parameters, velocity and attenuation, to classify clear and defective wood.

The effectiveness of the ultrasonic technique for detection of defects in a coniferous species (*Pinus ponderosa*) was evaluated in this research work. A prototype machine designed and constructed by the Forest Products Division of Perceptron was used for testing. Boards were passed between two rolling transducers that pressed on the edges of the board, one to send and one to receive. The received pulse is compared to the transmitted pulse. Small defects, such as tight knots or small internal splits, should affect attenuation or velocity making the defect detectable. If cut-off values can be established for these parameters, clear wood could be differentiated from defective wood.

2- OBJECTIVES

Find any difference in velocity or attenuation between pieces of wood with defects and pieces of woods that are free of defects.

Establish thresholds for wave velocity or attenuation in order to separate pieces of wood with defects from clear wood.

Determine the usefulness of this method when applied to an industrial sorting operation.

3- LITERATURE REVIEW

3.1- Fundamentals of sound

3.1.1- Definitions

Sound can be defined as a mechanical wave motion in a fluid or elastic medium. Mechanical waves, unlike the non-mechanical waves such as light and electromagnetic waves, require a solid, liquid, or gaseous medium in which to propagate. In fact sound waves propagate better in a solid than in a liquid or gas.

Adjacent particles or molecules induce the mechanical motion or vibration of a wave. This vibration produces a displacement on the particle. The maximum displacement from the point of equilibrium is defined as amplitude, and the number of vibrations per unit of time is defined as frequency. Each vibration is called cycle and a cycle per second is the measurement unit called a Hertz.

The medium resists the propagation of sound by internal friction. This causes the amplitude to decrease with time until the oscillation stops completely. This is known as damping. All media produce damping at different levels (Giancolli, 1980).

Each system vibrates at its natural frequency (resonant frequency), however a medium requires an external force to vibrate. When the external force creates frequencies that are the same as the natural frequency of the material, the amplitude of vibration and the energy transferred to the vibrating system is at a maximum. This phenomenon is known as resonance (Halliday and Resnick, 1981).

3.1.2- Type of waves

When the vibration of the particles is in the same direction of the motion of the wave, it is defined as a longitudinal wave. In this kind of wave the particles are compressed and expanded along the wave path. Longitudinal waves are the most suitable to detect internal flaws in solids and are the only kind of waves that can be transmitted in liquids and gases. When the particle vibration is perpendicular to the motion of the wave it is defined as transverse (shear) wave. Transverse waves are useful to detect flaws close to or on the surface of the piece. (Glickstein, 1960)

3.1.3- Wave velocity

The wavelength (λ) in longitudinal waves can be defined as the distance between two consecutive areas of compression or expansion, the frequency (f) as the number of waves that pass a point per second, and the wave velocity (V) as the velocity at which each compression area moves. These are related by

$$V = f * \lambda \tag{1}$$

Sound travels faster through materials with a higher modulus of elasticity (MOE) and slower through materials with higher density (ρ) (Frederick, 1965). These are related through the expression;

$$V = \sqrt{MOE / \rho} \tag{2}$$

These two relationships have been used in non-destructive testing to evaluate modulus of elasticity in wood.

3.1.4- Wave energy (Intensity)

Sound waves transfer energy from one point to another. The energy is measured in W/m^2, which is called intensity. Because intensity is energy which propagates in a periodic motion (in sound propagation) it can be expressed as follows:

$$I = 2\pi^2 V\rho f^2 A^2; \tag{3}$$

where; A = amplitude (m)

V = wave speed (m/s)

ρ = density of the material (kg/m^3)

f = frequency (1/s)

The intensity of one sound wave can be related to another. This relationship is defined as intensity level (β), and is measured in decibels,

$$\beta = 10 \log (I / I_o) \tag{4}$$

where I_o is the intensity of reference. Any reference intensity may be selected but in some acoustical work it is often the threshold of audibility (10^{-12} W/m^2) (Shortley and Williams, 1959).

3.1.5- Wave energy reduction

The amplitude and energy decrease with the distance traveled. This is called attenuation (Ensminger, 1973). In general, attenuation increases with the frequency. It is reported that attenuation in solids at ultrasonic frequencies varies from 10^{-3} dB/ft ($I/Io \cong 1$) to many tens or more dB/inch for some types of materials like plastic and cast iron (Frederick, 1965).

When a wave approaches an obstacle the wave can be reflected, refracted, and/or diffracted. The wave is reflected if it bounces back from the obstacle. But not all the sound energy is reflected, some is absorbed and transformed into thermal energy, and some continues into the obstacle. The wave, which continues travelling into the obstacle, may change in direction. This effect is called refraction. Diffraction is the property by which the sound can bend around the obstacle. The amount of diffraction depends on the size of the obstacle and on the wavelength (Giancolli, 1980). If the obstacle is a small fraction of the wavelength, there will be no reflection but diffraction. If there are many small obstacles, a large proportion of the energy may be scattered and can even disappear inside the piece. Two factors must be considered in the size of the obstacle; the dimension in the direction along the propagation path and the cross sectional area. It is the dimension along the propagation path that interrupts the wave, but it is the cross sectional area that determines the amount of reflection (Carlin, 1960). In practice, reflection, refraction, diffraction and absorption of energy also affect attenuation (Ensminger, 1973).

3.2- Ultrasonics

The audible range of human hearing varies from about 16 to 20000 Hertz. Ultrasonic waves are defined as those having a frequency above the range of human hearing (Carlin, 1960). Ultrasonic frequencies have short wavelengths that make them particularly useful for nondestructive testing. Low frequency waves with long wavelengths will easily bend around any small defect, producing no reflection. The characteristic high frequency of ultrasound also produces directional waves. Small transducers can direct these waves similar to light beams (Glickstein, 1960).

The source of energy for ultrasound wave generation is usually an electrical generator (oscillator). The oscillator can generate from 16,000 to several million Hz. The electrical energy is converted into acoustic energy by devices called transducers. The most important aspects of the transducer are the physical size and the coincidence of its resonant frequency to the output frequency of the generator (Glickstein, 1960).

3.3- Non-destructive testing methods using sound

The pulse method of nondestructive testing is the most common in industry. An intermittent wave or signal travels through the medium, reaches the receiving transducer, and is transformed into electrical energy that triggers the oscilloscope (Gooberman 1968). There are three variations of this technique; pulse-echo, pitch-catch and through transmission. The pulse-echo technique uses only one transducer that sends signals and receives the echoes from any interference. Pitch-catch method involves the use of two transducers usually mounted on the same holder, where one emits the signal when the other receives the reflected pulses. The through transmission method involves the use of two transducers located at opposite sides of the piece. In this method the signal passes through the region of interest (Ensminger, 1973). The through transition technique is the most appropriate for high-speed applications.

Measurement techniques for longitudinal waves are often based on two parameters, wave velocity and attenuation (Gooberman, 1968). The longitudinal wave velocity is called the stress wave velocity. This category can be separated in two subcategories depending on the origin of the wave: ultrasonic or impact-induced stress wave velocity. For an ultrasonic stress wave, an electrical or electronic generator produces the pulse, transit time is measured over a predetermined distance, and the average velocity is calculated. The impact-induced stress wave velocity instruments uses mechanical waves, which are generated by impacting the specimen on a free surface (Kaiserlik,1978).

3.4- Sound propagation in wood

According to McDonald (1978) the sound wave propagation is different in clear wood than in defective wood. Wave velocity and attenuation are the two parameters that are often studied to evaluate sound propagation in wood.

3.4.1- Wave velocity

To measure wave velocity the sensors or transducers are placed at two points on the piece and the time to travel from one point to the other is computed. The distance and time are used to calculate the wave velocity over a determined length of the piece.

3.4.1.1- Wave Velocity vs wood structure

Sound wave propagation through the wood is greatly influenced by the anisotropic nature of wood. Sound velocity is two or three times higher in the longitudinal direction than in the transverse direction. The annual ring orientation affects the sound propagation in the transverse direction. The velocity is lower in the tangential direction than in the radial direction. The lowest velocity is found when the annual ring orientation is at an angle of 45° to the direction of wave travel (MacDonald, 1978). Due to the cell arrangement, at 45° to the ring angle there is more resistance to the pulse while in the radial direction there are more "paths" created by the ray cells.

3.4.1.2- Wave velocity vs moisture content

Gerhards (1977) determined that the speed of sound decreases almost linearly with the moisture content up to the fiber saturation point. The amount of change in speed of sound becomes smaller from the fiber saturation point to a moisture content of 80%, and changes very little thereafter.

3.4.1.3-Wave velocity vs temperature

Increases in temperature decrease the speed of sound (James, 1961). He reported that internal friction is at a minimum between 0° and 200° F and moisture content from about 2 to 28%.

3.4.2- Attenuation

In general, attenuation increases with frequency (Bucur and Feeney, 1991). However, there are other factors that affect attenuation as well, such as wood structure and moisture content.

3.4.2.1- Attenuation vs. wood structure

Bucur and Feeney (1991) applied frequencies from 100 to 1500 kHz to chestnut (*Aesculus hypocastanum*) and concluded that attenuation was greatest in the transverse direction and least in the longitudinal direction. The directional dependence can be explained by the orthotropic wood structure in which the longitudinal cell arrangement acts as "highways" where the sound wave propagates, giving minimum attenuation. The radial direction presents radial paths, which act the same as longitudinal cells but in less proportion. On the other hand, the tangential direction presents the least organized structure producing more scattering of sound waves (Burmester, 1967).

The two main causes of attenuation are scattering and absorption. In wood, absorption due to the thermoelastic effect or damping is reported to be less important than scattering. Scattering is related to the grain size, which in the case of wood is the fiber length or diameter (Bucur and Bohnke, 1994).

3.4.2.2- Attenuation vs moisture content

Based on studies of seven wood species Sakai et al. (1989) reported that attenuation due to scattering is independent of moisture content up to the fiber saturation point. Attenuation rapidly increases above the fiber saturation point because the free water trapped in the intercellular space produces additional acoustic loss.

3.5- Non-destructive evaluation in wood

The stress wave velocity through wood is related to its density and modulus of elasticity. The strength properties of wood can be indirectly derived based on a known density and wave velocity. This method is presently used for testing solid wood, wood-based composites, and non-wood products (Ross et al, 1992). The same authors (1994) concluded that this technique would be useful to detect wetwood in wood. They reported that 93% of severely infected wetwood was nondestructively identified in red oak using the stress wave technique. An impact hammer was used to produce the sound wave and the time and velocities were computed as they passed through clear or infected wood. The frequency used was not reported, but since an impact hammer was used it should have corresponded to the sonic range of the spectra.

This technique has been proven to work when there are significant changes in the density or strength of the material. However, it has been less successful at detecting small checks that do not cause great changes in material properties. Ross (1985), experimenting with the effect of a saw kerf on wave travel time and attenuation, reported that travel times were identical for clear wood and wood with a saw kerf; however, an increase in wave attenuation was observed. The wave was produced by an "impactor," which is expected to produce a long wavelength. Nevertheless, Hoyle and Rutherford (1987) state that low velocity readings may occur due to checks because the wave must follow a circuitous route around the check.

There is no information on the frequencies or methodology applied to arrive to this statement. Similarly, Fuller et al. (1994), using a rolling transducer and an electronic pulse generator, reported that sound transmission time perpendicular to the grain is significantly increased by the presence of honeycomb and surface checks.

Non-metallic materials, such as wood, create difficulties in flaw testing because of the reflection and refraction of the sound beam occurs due to the irregular structure. Damping is so strong that penetration is only possible for relatively low frequencies. The strongest damping occurs when the grain size (fiber dimension) falls into the region of a half wavelength. At higher frequencies the damping is so strong that the penetration in wood is not possible (Burmester, 1967).

McDonald (1978) reported that frequencies usually used with wood range from 150 kHz to 1000 kHz. At lower frequencies (150-200 kHz) the detection of flaws is not very precise. Higher frequencies (500-1000 kHz) permit better definition of defects. Beall (1996) reports that the usable frequencies for wood-based material are about 100 to 200 kHz.

It follows that the frequency, the nature and size of the fibers, the ring orientation, fiber angle, density and the grain direction are critical to check detection if attenuation is the main parameter. If wave velocity is used, then moisture content is also important.

4- MATERIAL AND METHODS

4.1- Material

Two hundred and fifty ponderosa pine (*Pinus ponderosa*) boards, 6 to 8 feet in length, 6 inches in width and 1½ inches in thickness were donated by Crown Pacific in Prineville, Oregon. They were collected over a 30-day period when green, then transported to Oregon State University.

4.2- Equipment

The dryer was an aluminum prefabricated laboratory kiln. It is indirectly heated with steam to control the dry-bulb temperature and has steam spray and venting to control the wet-bulb temperature.

A resistance type moisture meter, with pin electrodes that penetrate the wood using a hammer type device, was used to measure moisture content of dried wood.

A prototype machine made by the Forest Products Division of Perceptron (Plymouth, MI) was used to test the boards ultrasonically. In this machine, a board passes between two roller transducers, one sends the signal through the board in the 6-inch direction and the other receives it. Thus, each transducer presses on opposite edges (the 1.5 inches thick side) of the board. This equipment could generate sound waves in the range of 120 to 200 kHz and apply an ultrasonic pulse every 0.05 inches along a board at a speed of 500 ft/min.

This prototype can analyze different parameters. Attenuation is calculated as the insertion loss (IL). When the signal is more attenuated, a more negative value is obtained. Insertion loss is calculated using equation 5,

$$IL=10\log(E_r/E_t)-G \qquad (5)$$

where,

IL = Insertion Loss, dB

E_r= energy received by the receiving transducer, volts

E_t= energy input to the transmitting transducer, volts

G= the receiver gain, dB.

The time of flight parameter is the elapsed time for the sound to travel from the transmitter to the receiver and for the receiver to reach 40% of the maximum amplitude.

The pulse length or pulse duration indicates how compact the signal is. The lowest pulse duration corresponds to the most compact signal. The pulse length was defined as 1.25 times the time required for the received wave energy to rise from 10% to 90% of its final energy.

Finally the defect index , which is a parameter proprietary to Perceptron that combines insertion loss and pulse duration was calculated. The prototype produces an ascii file of the measured parameters as a function of the distance along the board. An example of these in graphical form is shown in Figure 1.

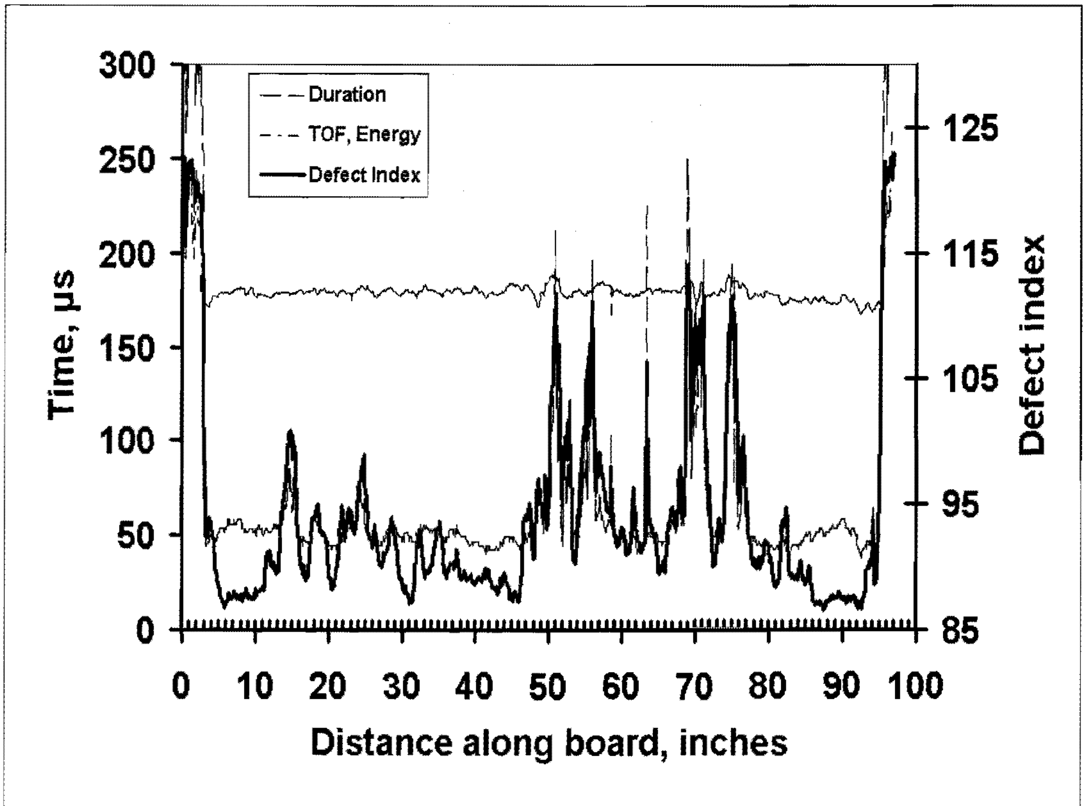


Figure 1. Example of a graph for a board showing pulse duration, time of flight and defect index versus distance along the board.

4.3- Board preparation

The green boards were randomly assigned to two groups. The piles were stacked using 1.9 cm thick stickers spaced every 66 cm. Spaces of several inches occurred horizontally between adjacent boards. This preparation was done to assure similar conditions of moisture content and moisture distribution for each board at the end of the drying process.

4.4- Drying, storage and shipping

The first charge was dried immediately using a low temperature, while the second charge was dried two weeks later using a higher temperature to attempt to force internal checks or other defects to appear. The objective of drying at two different schedules was to have both defective and non-defective boards to analyze. Tables 1 and 2 show the low and high temperature schedule used, respectively.

Table 1. Low temperature drying schedule.

Dry bulb,°F	Wet bulb, °F	Time, hr
160	140	24
165	140	24
170	140	72
*170	170	30
170	140	16

* Conditioning treatment

Table 2. High temperature drying schedule.

Dry bulb,°F	Wet bulb,°F	Time, hr
180	170	12
200	180	12
200	150	61

The target final moisture content was 12% in each case. There was no conditioning treatment for the high temperature drying schedule. After drying, the boards were stored on stickers at room temperature and humidity conditions for 9 months. Finally the boards were solid piled and transported to Brainerd, Minnesota for the ultrasonic testing.

4.5- Ultrasonic testing

All boards were tested at least once using a frequency of 200 kHz and a speed of 500 feet/min. Moisture content was measured using a resistance-type moisture meter on every tenth board. All tests were run at room temperature and the data collected (pulse duration, time of flight, insertion loss, defect index, and distance along the board) for each board were stored on a disk.

4.5.1- Board identification

Each board was assigned an identification number for each pass through the machine. The numbers were written on the top face at the end that first enters the machine (Figure 2). Each identification number then corresponds to the name of the data file.

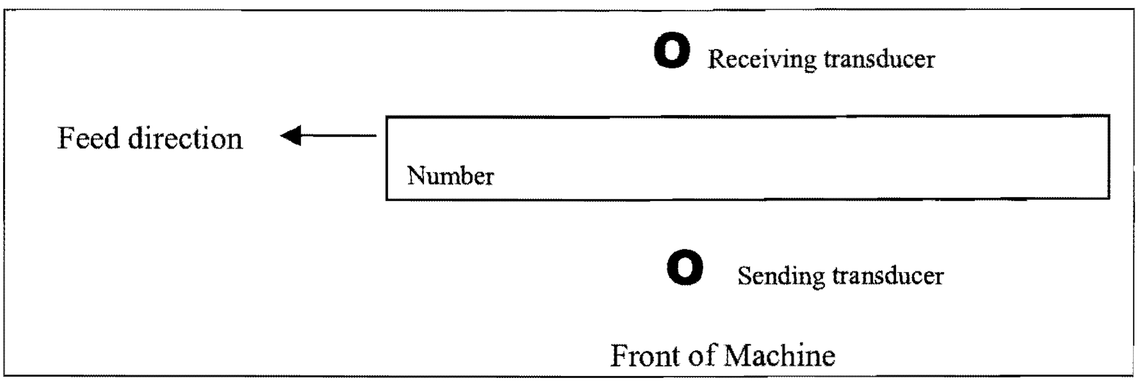


Figure 2. Board identification procedure.

4.5.2- Effect of frequency

The prototype machine was set at three different frequencies to examine the influence of frequency on the measured parameters. The frequencies were the maximum possible, 200 kHz , 160 KHz, and the minimum, 120 kHz. Twenty-four boards were tested at these three frequencies.

4.5.3- Repeatability of measurements on a board

Ten boards were passed through the prototype three times each with the boards in the same orientation relative to the machine. The machine was set to a frequency of 200 kHz for each pass. The consistency of data was examined for each board to determine repeatability of the technique.

4.5.4- Repeatability of measurements with boards in different orientations

Twenty-five boards were passed through the machine multiple times using different orientations to determine if the attenuation depends on feed orientation. The board was turned end-for-end between each pass and also rotated 180° around its longitudinal axis between orientations 2 and 3. Thus, the same face is up in orientations 1 and 2 and in orientations 3 and 4. The sending transducer contacts the same edge in orientations 1 and 4 and in orientations 2 and 3. Also, the same end of the board was first presented to the machine in orientations 1 and 3 and in orientations 2 and 4. In this way all possible orientations were tested. The objective was to observe if different edge and face positions affect the consistency of the data on each board.

4.5.5- Effect of end checks

During testing it was noted that a large attenuation was typical near the end of the board. To be sure this was attributable to end checks, one board was cut into two pieces and each piece was rerun (Figure 3). The cut was made at a position on the board with low attenuation. If increased attenuation was observed at the fresh-cut ends, it would indicate that an effect due to the end of the board was causing it rather than end checks.

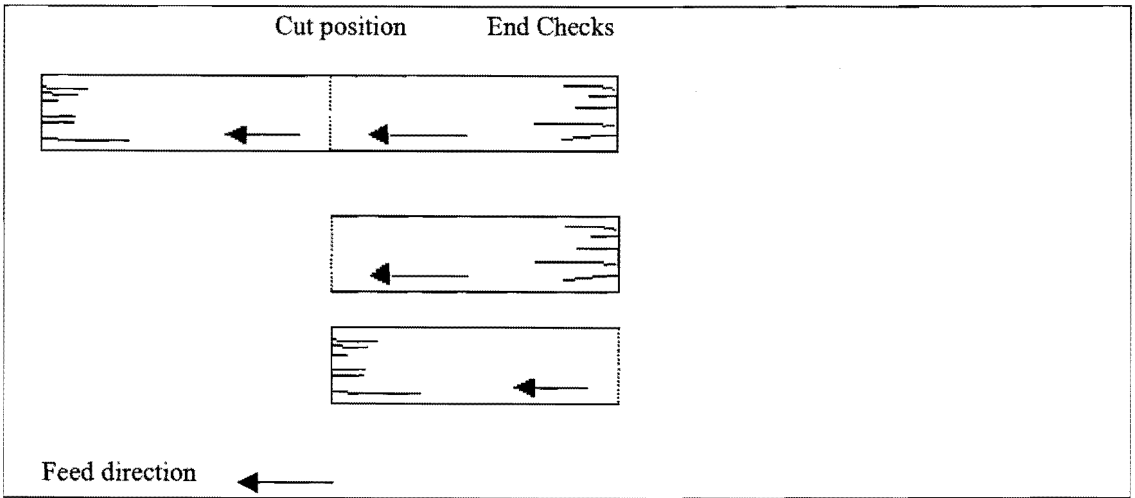


Figure 3. Procedure to evaluate the signal response at the ends of the board

4.6- Determination of wood properties

The boards were transported by truck to the wood drying laboratory at Oregon State University where additional measurements and calculations were done.

4.6.1- Measurements

Moisture content, weight, board dimensions (length, width, and thickness) and ring angle were measured. The moisture content was measured using a resistance type moisture-meter set for ponderosa pine and ambient temperature. Each measurement was taken at the center of the board at a 1-inch depth. The dimensions were measured using a tape measure and the weight using a scale with an accuracy of 0.01 lbs.

The ring angle was measured at each end of the board using a custom-made, clear Plexiglas protractor. This is defined as the angle between an imaginary line from the board to the pith of the tree and a second imaginary line from perpendicular to the face of the board. The lines intersect at the center of the end (transverse face) of the board. The location of the pith is estimated from the ring curvature. A ring angle of 0° indicates flat sawn and 90° indicates quarter sawn. Ring angle was measured at each end and averaged.

4.6.2- Calculations

The volume (V, ft^3) of each board was calculated from its dimensions. There was no wane on the pieces. The oven-dry weight of the board (W_{od}, lb) was estimated based on the measured weight (W, lb) and moisture content (MC, %).

$$W_{od} = \frac{W}{(1 + MC/100)} \tag{6}$$

The wood density (ρ_{od}, oven-dry basis) was then calculated as

$$\rho_{od} = \frac{W_{od}}{V} \tag{7}$$

4.7- Visual inspection of defects

Defects were classified in six different groups: internal checks, surface checks, knots, ring deviations or abnormalities, pitch pockets and end checks. An internal check was defined as any internal crack or discontinuity in the wood. A surface check was defined as a split on a face of the board and an end check was any split visible at the ends of the boards. A pitch pocket was defined as a void space produced by resin accumulation. Any deviation of the ring pattern was classified as a ring abnormality.

Seventy-five randomly-selected boards were visually inspected for defects. Three methods were chosen to evaluate the presence of defects: cross cutting, resawing and slicing. Twenty-five boards were assigned to each of these methods. Finally, the best visual inspection method was selected according to its potential to identify and locate defects.

4.7.1- Cross cutting

One-cm-long sections were cross cut from boards using a radial-arm saw. A stain (oil-based walnut furniture stain) was applied to one of the cut end grain surfaces. If small cracks were present, the stain wicked through and was visible on the opposite surface. The pieces were also bent to observe any kind of split or defect.

Three to nine locations, with pulse durations longer than 200 μs were cross cut on each board, excluding the end check signals, to check for defects. Three locations per board, where the pulse duration was shorter than 150 μs, were also examined (Figure 4).

4.7.2- Resawing

Boards were resawed (cut through the 6-inch direction) to two halves to expose the interior of the board. The four faces were planed to produce smooth surfaces to better identify defects. Then the pieces, now 0.63 inches in thickness, were visually inspected and the type, position, and size of defects were recorded. Finally, the visual inspection category (for example clear, internal check, etc.) was added to the data set containing the parameter values from ultrasonic testing so that statistical analysis could be performed.

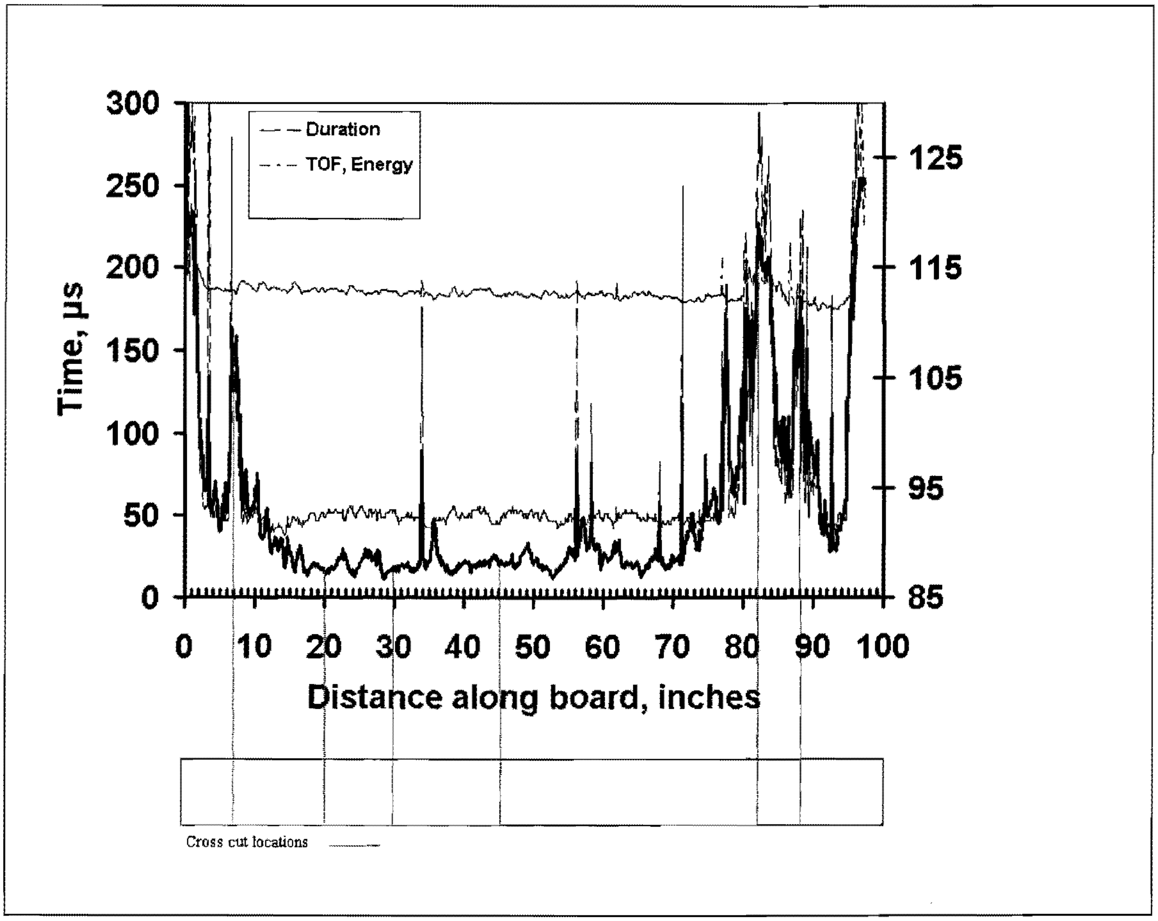


Figure 4. Example showing the locations where a board was cross cut relative to the pulse duration parameter.

4.7.3- Slicing

Boards were sliced into 0.06-inch-thick veneer to expose the interior of the board at several depths. Each veneer was visually inspected for presence of defects using a light table. Where defects were suspected, a stain was applied to one side of the veneer, similar to what was done in the crosscut method. The type, position, and size of defects were recorded. Finally, the visual inspection category (for example clear, internal check, etc.) was added to the data set containing the parameter values from ultrasonic testing so that statistical analysis could be performed.

4.8- Data Analysis

4.8.1- Effect of frequency

Two approaches were used to check the effect of frequency on the parameters. One was a graphical approach, in which the values of the parameters were graphed at the three different frequencies and then visually compared to each other. The second approach was using linear regression. The parameter values at the different frequencies, for a given point, should be highly correlated if the ultrasonic testing is consistent at each frequency. Three correlation coefficients were obtained, one for regression of parameter values obtained at a frequency of 200 kHz on parameter values obtained at 160 kHz, one for regression of parameter values obtained at 200 kHz on parameter values obtained at 120 kHz, and the third for regression of parameter values obtained at a frequency of 160 kHz on parameter values obtained at 120 kHz.

4.8.2- Repeatability of measurements with boards in the same orientation

Two approaches were used to analyze the data for machine repeatability. One was a graphical approach, in which the values of the parameters (defect index, pulse duration and time of flight) for each of the three passes of the board were plotted and then visually compared to each other. The second approach was using linear regression.

For the linear regression, the data for all 10 boards were pooled. Each board test point provided a set of three matched data points, one from each pass through the machine. The data from one replication was regressed against the data from the other replications: one to two, two to three, and three to one. The correlation coefficients were used to estimate the repeatability, with a high correlation indicating good repeatability.

4.8.3- Repeatability of measurements with boards in different orientations

The same procedure as described in the previous section was used to assess repeatability in different orientations. Graphs of the parameter values were produced for the four different positions tested and compared visually. Linear regression was performed for the data from one orientation against the other three, producing six regression coefficients.

4.8.4- Evaluation of signal versus defect

An analysis of variance procedure was used to examine differences in the parameter values (pulse duration, time of flight, and defect index) among the types of defects and clear wood. A difference in the value of a parameter between wood types (clear versus checked, for example) would indicate that the wood type could be sorted. Only the results of the visual inspection on the sliced boards were used for the analysis. Categories for the ANOVA included clear wood, internal checks, end checks, surface checks, knots, grain deviation and pitch pockets. The independent variables were time of flight, insertion loss, pulse duration and defect index. Once a significant difference on the parameters among groups was detected a pair wise comparison was done using the Bonferoni method at a 95% confidence level.

4.8.5- Ability to predict defects

Contingency tables were used to evaluate the ability of the ultrasonic technique to predict the presence of defects. Again the slicing method data was used to construct this table. Thresholds for time of flight, pulse duration and insertion loss were used to classify presence or absence of defects. The thresholds were the mean values of clear wood for each parameter. This information was compared with visually-observed presence or absence of defects in the boards. Four categories were identified for the tables: indicated present by machine and visually present (MpVp), indicated present by machine but visually absent (MpVa), indicated absent by machine and visually absent (MaVa) and indicated absent by machine but visually present (MaVp) (Fig 5).

	Vp	Va
MP	MPVp	MPVa
MA	MAVp	MAVa

Figure 5. Contingency table arrangement.

4.8.6- Analysis of causes for erratic signals

It was noted that some boards had very irregular attenuation with position while others had low attenuation, all with no apparent relationship to defects. For example, the two graphs in Figure 6 are each for boards with no visual defects. To try to identify a cause for this, the signals from the boards were classified in three groups:

noisy erratic signal, intermediate, and smooth signal. A board's graph was considered erratic when it showed drastic peaks and valleys on the parameter values all along the board. The graph was considered smooth when it shows mainly a flat configuration, and as intermediate when it could not easily be placed in one of the other two groups. Sixty-nine boards were classified in one of these three groups: forty as smooth, twenty-three as erratic and four as intermediate. Analysis of variance was used to evaluate any differences in density or ring angle among the three different groups of signals. There was not enough variability in moisture content for it to be evaluated.

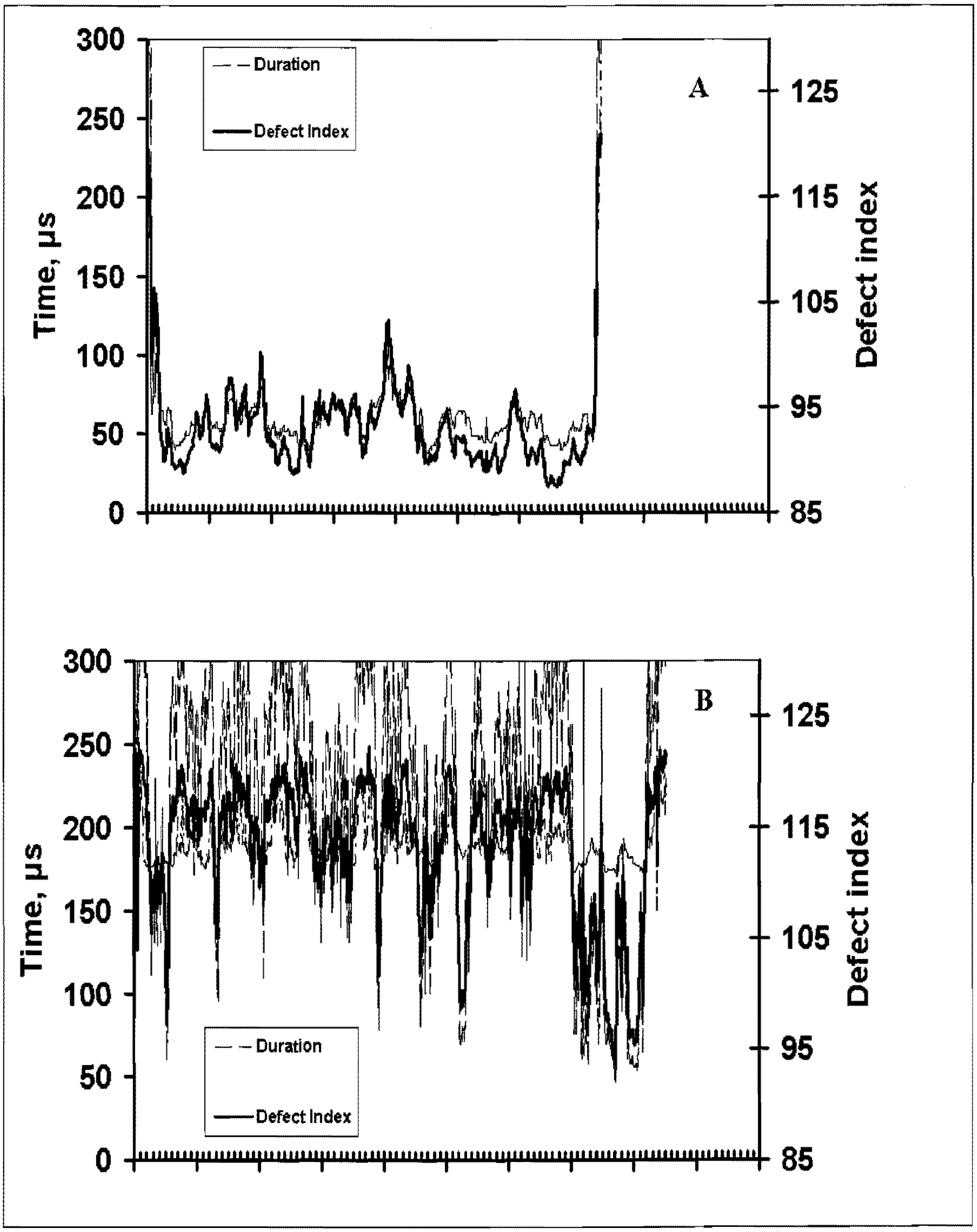


Figure 6. Examples of boards with consistent (A) and erratic (B) signals.

5- RESULTS AND DISCUSSSION

5.1- Visual inspection methods

Among the three methods used to visually inspect the lumber, fewer points were inspected using cross cutting. This was due to the effort involved in cross cutting with the radial arm-saw and the relatively few locations that could be inspected. On the other hand, resawing or slicing allowed the entire length of the board to be visually scanned for defects with relative ease. For these methods, each inspection location was considered to be 0.05 inches apart, the resolution of the ultrasonic test machine. Table 3 shows the number of locations inspected using each method and the defects found. Defects were most easily identified and classified using the slicing method because the veneers allow examination of all the internal parts of the board. However, there is a greater chance that defects are created in the slicing process than in the other two methods. However, this did not appear to be a problem and the slicing method is used in later parts of this report to evaluate the ultrasonic technique.

Table 3. Defects identified though visual inspection by the three methods.

	Method		
Visual inspection	Resawing	Slicing	Cross cutting
(groups)		(Counts)	
Clear wood	20229	20605	121
Int. checks	724	381	1
End Checks	1306	977	2
Grain deviation	21	39	14
Knots	0	62	3
Pitch pockets	186	262	2
Surface checks	123	53	4
Total	22589	22379	147

5.2- Effect of frequency

The effect of frequency on defect index can be observed in Figure 7. Visual examination indicates that the trends for defect index are consistent among the three frequencies. Figure 7 also shows that greater attenuation (as indicated by a greater defect index) occurs at a higher frequency, in agreement with the conclusion of Bucur and Feeney (1991).

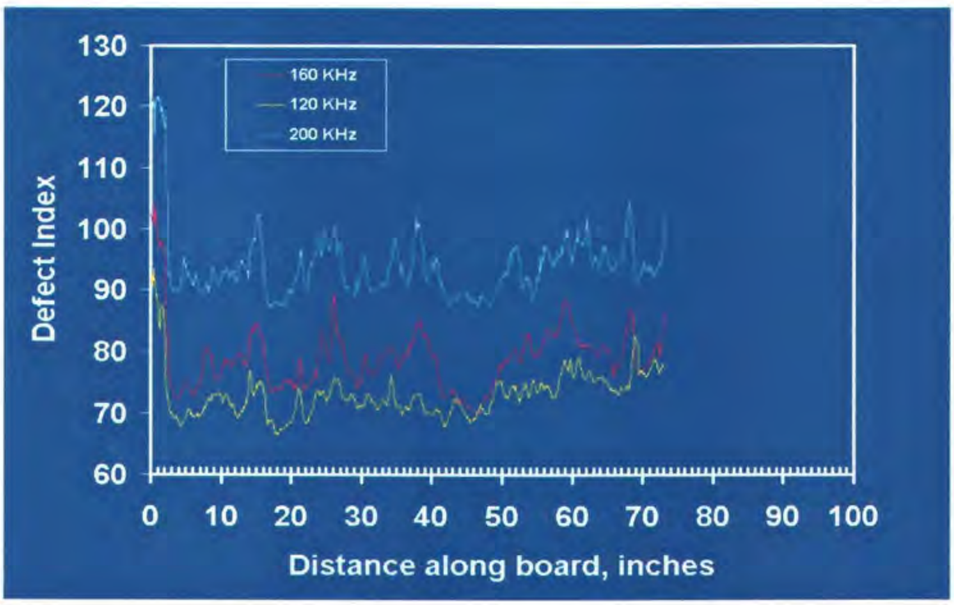
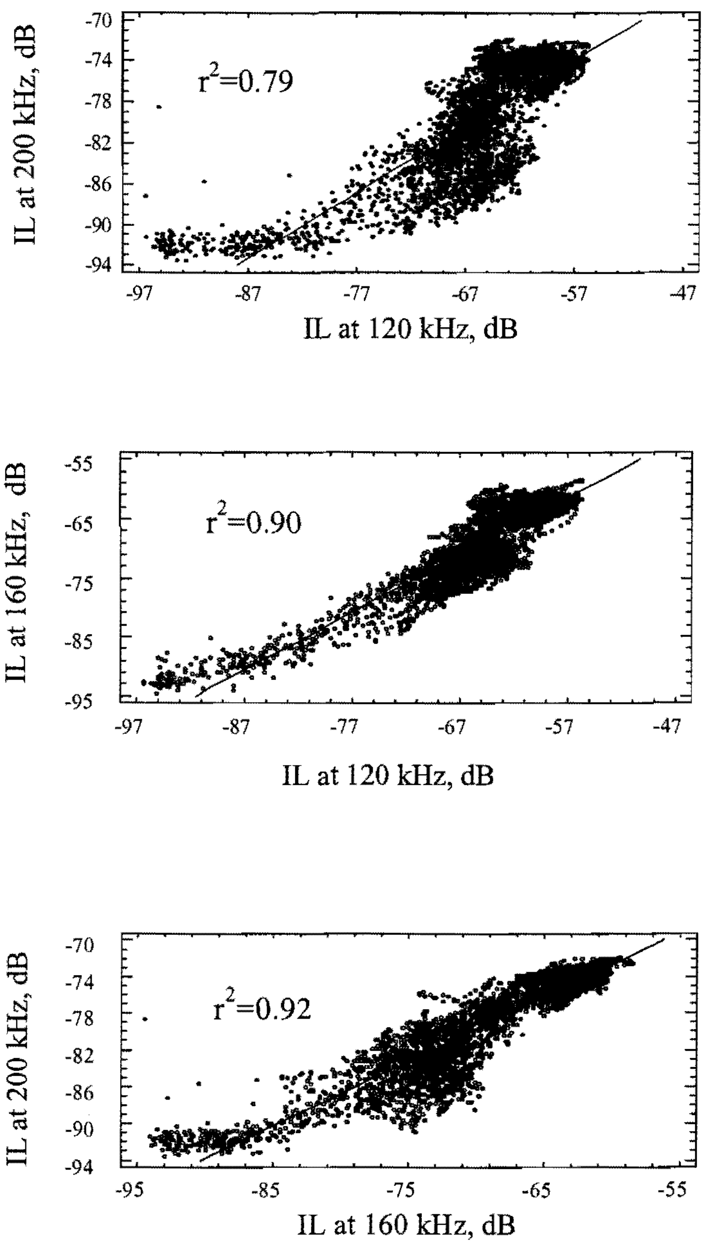


Figure 7. Defect index values for three different frequencies tested on the same board

Figure 8 shows the relationships between insertion loss at different frequencies for each observation. The correlation coefficients indicate that insertion loss values between 200 and 160 kHz and between 160 and 120 kHz are more correlated than between 200 and 120 kHz.



IL= insertion loss

Figure 8. Scatter plots of insertion loss values at one frequency versus insertion loss at a second frequency.

The correlation coefficients were calculated assuming that the prototype tests exactly the same point each time the board is run through, but the points tested are off for about 0.03 to 0.06 inches in most of the cases. This displacement does not affect very much the consistency of the output.

The consistency of the parameters values within the range of 120 to 200 kHz suggests that frequency is not critical within this range. Because the frequency is not critical, the highest frequency is preferred because it should have higher sensitivity.

5.3- Repeatability of test measurements

A very high degree of agreement can be observed on the values of defect index for different testing repetitions on the same points of the same board in the same orientation (Figure 9). The correlation coefficients for defect index values between different repetitions (Figure 10) show high consistency among the different repetitions of the same board at the same orientation.

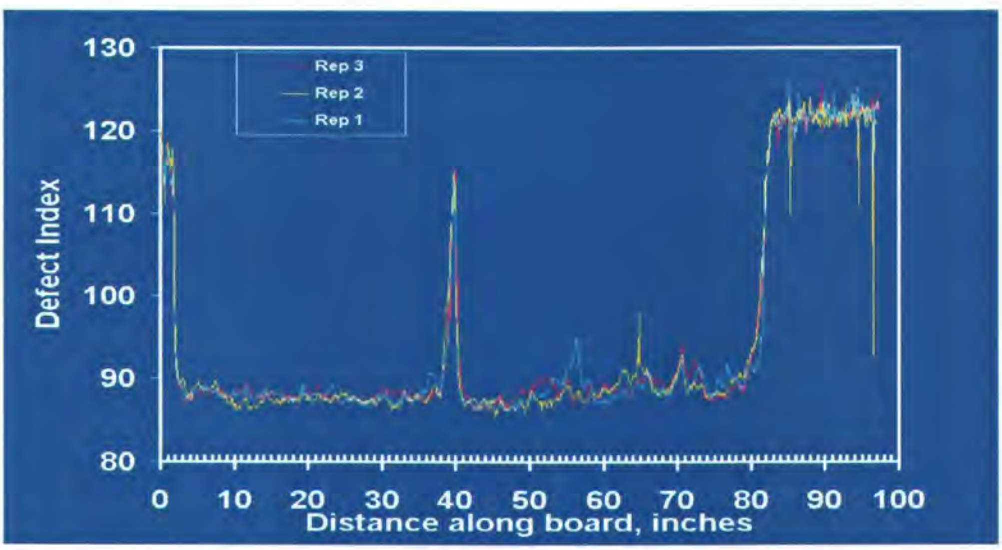


Figure 9. Defect index versus position for three repetitions on a board tested in the same orientation and feed direction. Frequency was 200 kHz for each repetition.

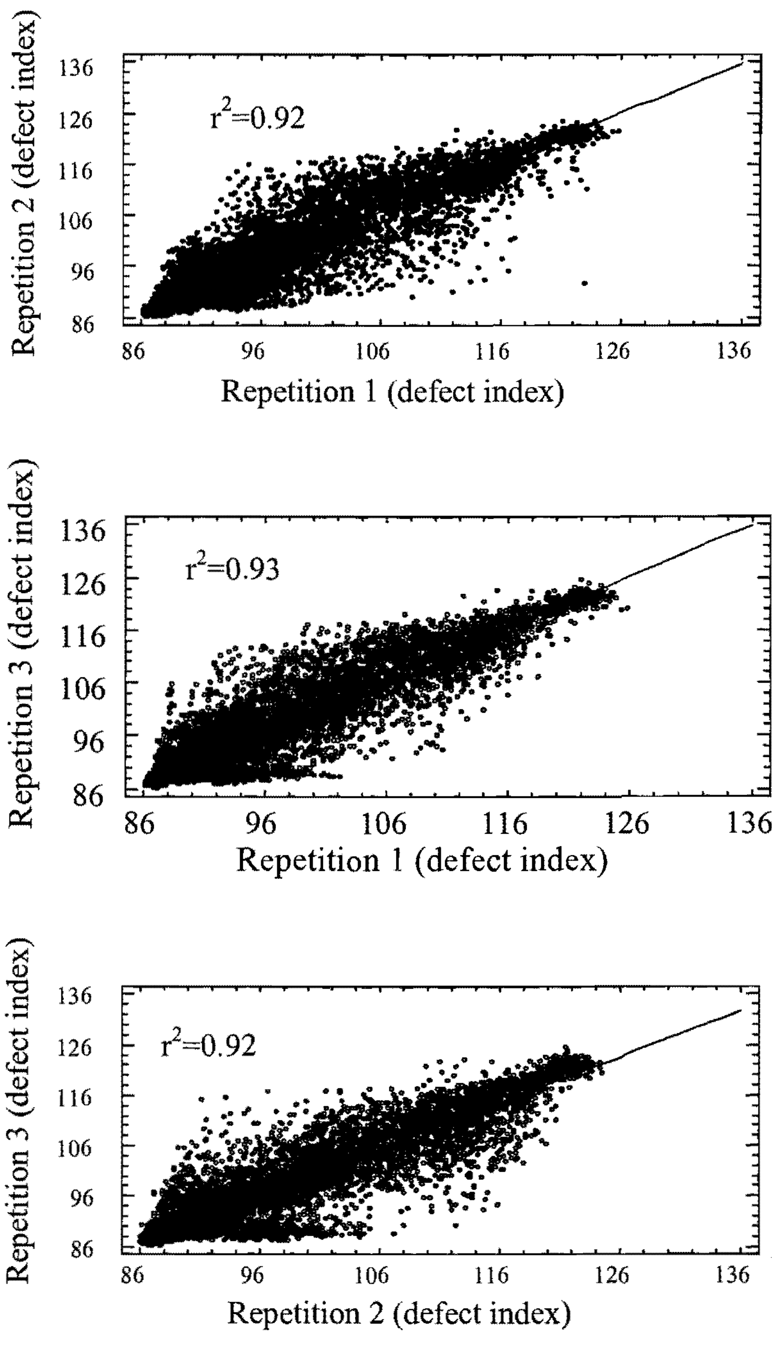


Figure 10. Scatter plots of defect index of one repetition versus another for 10 boards.

The distribution of correlated points (Figure 10) shows some points outside the linear trend when comparing the first test output (repetition 1) with the second (repetition 2) and the second with the third, but in general they show high agreement, which is consistent with the correlation coefficient values. This indicates that the ultrasonic test technique produces repeatable results and that it is likely that the peaks in the values correspond to a wood characteristic.

5.4- Repeatability of measurements with boards in different orientations

The correlation between defect index for each of the four feed orientations is shown in Table 4. All indicate moderately high repeatability. The correlation is better when both the feed direction and edge in contact with the sending transducer are changed (orientations 1 to 2 and 3 to 4, r^2 =0.78 and 0.85). This is not readily explained because the distance indices are less likely to be repeatable between these orientations. When comparing orientations 1 or 3 to 2 or 4 (r^2 = 0.73 and 0.74) the distance index starts at the same end of the board and a higher correlation would be expected.

Even though all of these correlations for attenuation are lower than when the same board orientation through the machine is repeated (r^2 = 0.92 to 0.93) as described in the previous section, one would still expect the defect index to be indicative of a board property because low and high attenuation occurs at repeatable points along the length of the board regardless of how it is presented to the machine.

Table 4. Coefficients of correlation for defect index among different board orientation

	ORIENTATION 2	ORIENTATION 3	ORIENTATION 4
ORIENTATION 1	0.78	0.73	0.69
ORIENTATION 2	-	0.70	0.74
ORIENTATION 3	-	-	0.85

5.5- Effect of end checks

High values of pulse duration, insertion loss, and defect index were observed at the ends of most of the boards. To ensure that these high values were due to end checks and not to end effects, one board was run through the machine then cut in half and rerun again. Figure 11 is a graph of wave travel time, pulse duration and defect index versus board position before the board was cut in half at the 48" point on the board. Figure 12 is similar data for the two halves. Zero inches in Figure 12-A and 48 inches in Figure 12-B correspond to the location where the board was cut. There was no end checking at this position because this location was at the center of the board during drying. Both before and after cutting, the signal is low, consistent with the absent of end checks. This indicates that the high attenuation observed at the end of most boards is due to end checks and not an artifact of the measurement technique.

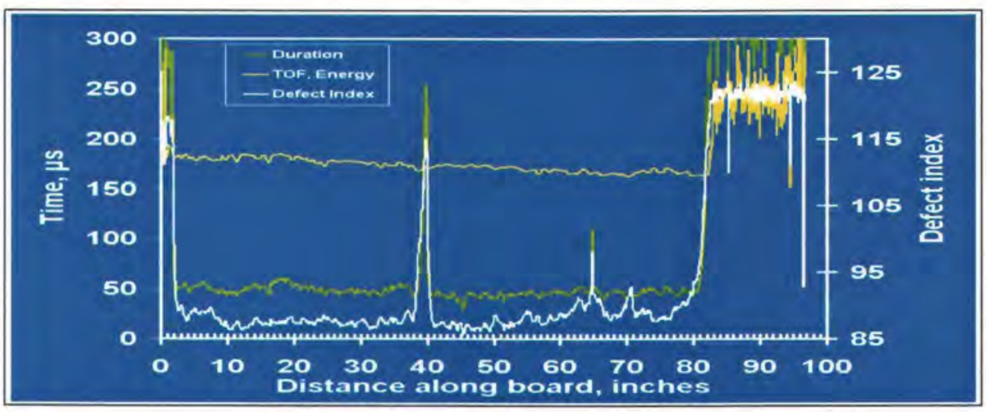


Figure 11. Parameter values for first run of the board, before cutting.

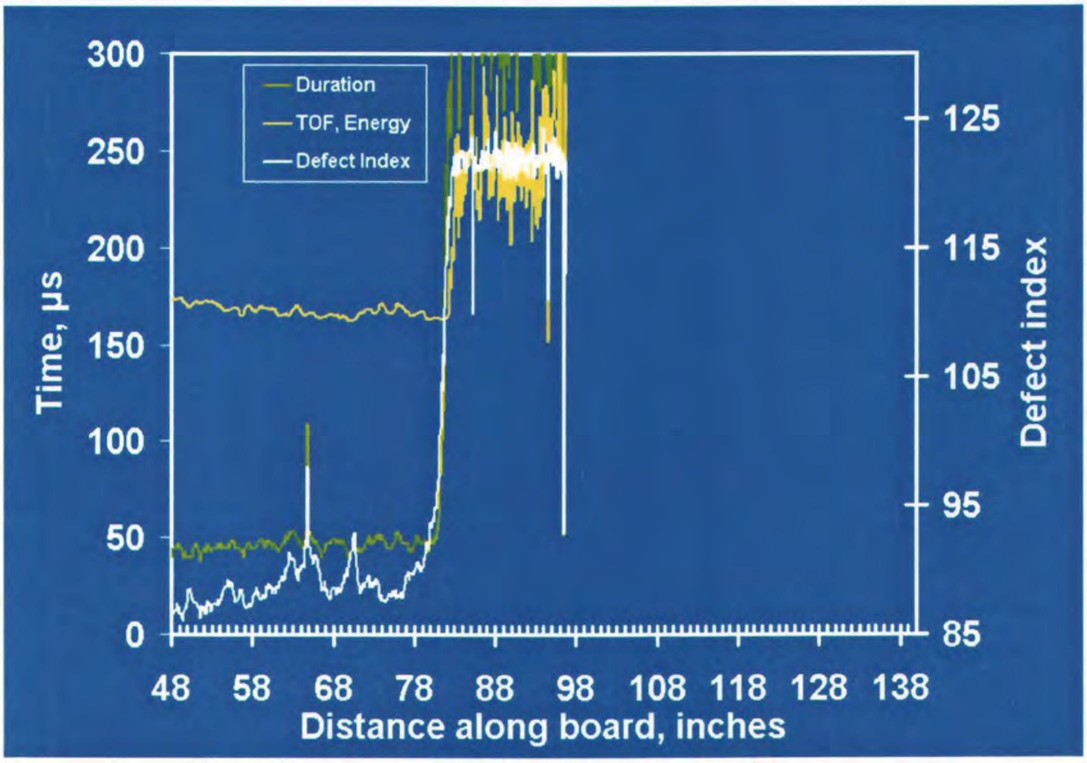


Figure 12-B

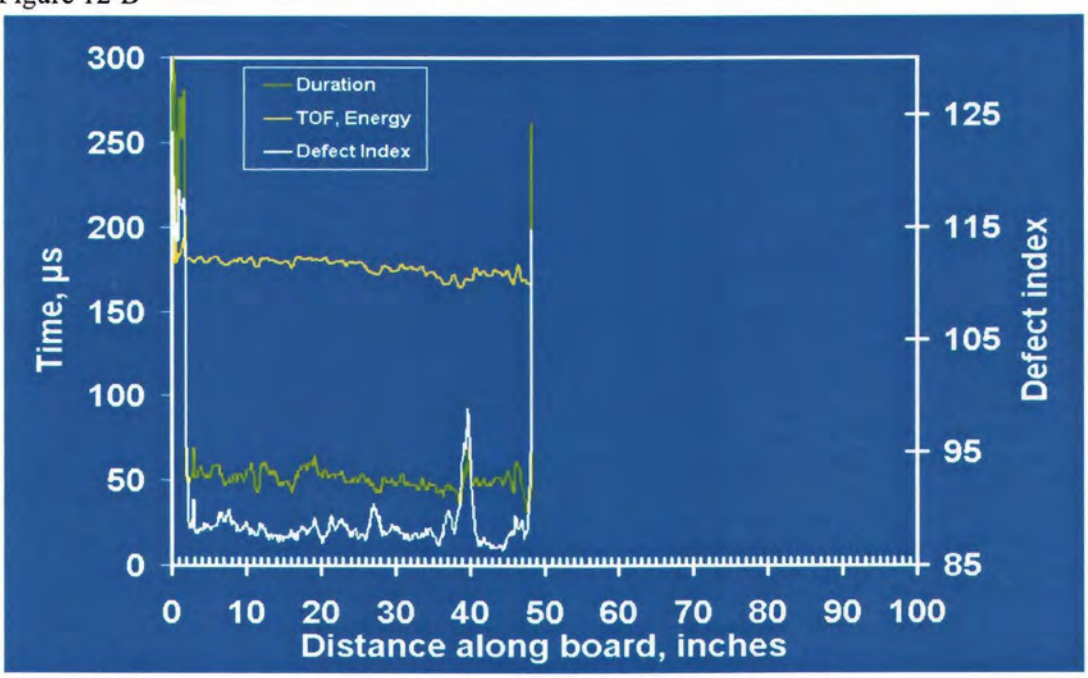


Figure 12-A

Figure 12. Output for the board shown in Figure 11 after being cut in half.

5.6- Effect of defects on signal

Table 5 indicates how each type of defect affected the parameters measured. The values in Table 5 are from the inspection method in which the boards were sliced. An analysis of variance (ANOVA) indicated that at least one defect type affects each parameter (p-value for F test is <0.001 for all parameters).

Table 5. Mean value of each parameter by type of wood visually observed in sliced boards.

Visual Inspection	Parameter				
	Time of Flight	Pulse duration	Insertion Loss	Defect Index	n
Clear wood	233.1	89.0	80.0	97.4	20,605
Internal Check	251.4	166.8	84.5	106.7	381
End check	268.1	241.3	87.8	114.4	977
Grain deviation	233.6	89.6	81.7	98.9	39
Knot	237.2	95.0	80.6	98.0	62
Pitch pocket	233.7	109.1	80.6	99.5	262
Surface Check	255.8	207.1	86.2	111.9	53
Total					22,379

Clear wood has the shortest time of flight and pulse duration. It also has the least attenuation (presented as insertion loss) and the smallest defect index. Each of these would be expected because clear wood between the transducers should provide the best pathway for the acoustic signal.

The results of the Bonferroni paired test to compare the effect of each wood type on each parameter are shown in Table 6. The time of flight and the insertion loss were significantly affected by all types of checks (internal, end, and surface), but not by the other parameters. Time of flight should be the parameter least affected by the wood characteristics, unless a discontinuity in the wood structure causes the wave to travel extra distance. Insertion loss, or attenuation, was also affected by discontinuities.

Table 6. Differences in parameter means between clear wood and defective wood

Group comparison	Parameters			
	Time of Flight(μs)	Pulse Duration(μs)	Insertion Loss (dB)	Defect index
Clear wood vs Internal check	*-18.36	*-77.75	*-4.49	*-9.33
Clear wood vs End check	*-35.06	*-152.31	*-7.82	*-17.01
Clear wood vs Grain deviation	-0.47	-0.61	- 1.75	-1.50
Clear wood vs Knot	-4.13	-6.03	- 0.58	-0.56
Clear wood vs Pitch pockect	-0.59	*-20.12	- 0.59	*-2.12
Clear wood vs Surface check	*-22.74	*-118.06	*-6.11	*-14.50

* Statistically significant at 95% confidence level

In addition to all types of checks, pitch pockets significantly affected pulse duration. Pulse duration is a measure of the scattering of the acoustic signal due to a discontinuity and this appears to be occurring in this data.

Knots did not affect any of the parameters; however, there were very few knots in the boards (see Table 3) and those that were present tended to be small and tight (intergrown). This agrees with the findings of Burmester (1967). Often they appeared at the corner of the piece (where an edge and a face meet) where detection would be difficult. Therefore it is not surprising that they were not detected. Grain deviations were minor irregularities from arcs in the growth rings and did not signify major changes in the cell arrangement or density of the wood. Grain deviation did not affect any of the parameters, probably because there is no discontinuity in the wood. This characteristic would not be a defect in manufacturing.

Even though there are statistically significant differences between some visual inspection group means their distributions overlap due to the great range of variation inside each group (Figure 13). In practice, this would make it difficult to separate most types of wood. However, it appears that end and surface checks might be successfully separated from clear wood. In fact, the best use for this technique might be for a producer to combine it with the knowledge that end checks, if they occur, are always at the end of the board and use defect index or insertion loss to determine how far to cut back to obtain clear wood.

5.7- Accuracy of prediction using thresholds

Table 7 shows the occurrences of defects and clear wood and their classification based on threshold values. The thresholds were selected to be the mean of the parameter value in clear wood. While somewhat arbitrary, parameter values greater than these means often indicate the presence of defects based on Figure 13. It is recognized that this may result in half of the clear wood being rejected (assuming a normal distribution), but a higher value would miss many of the defects.

Comparison of the resulting classification with the actual presence or absence of defects gives information about the accuracy of the test. Few internal checks and other defects were actually visually present compared with the large amount of clear wood points (Table 7 and Table 8).

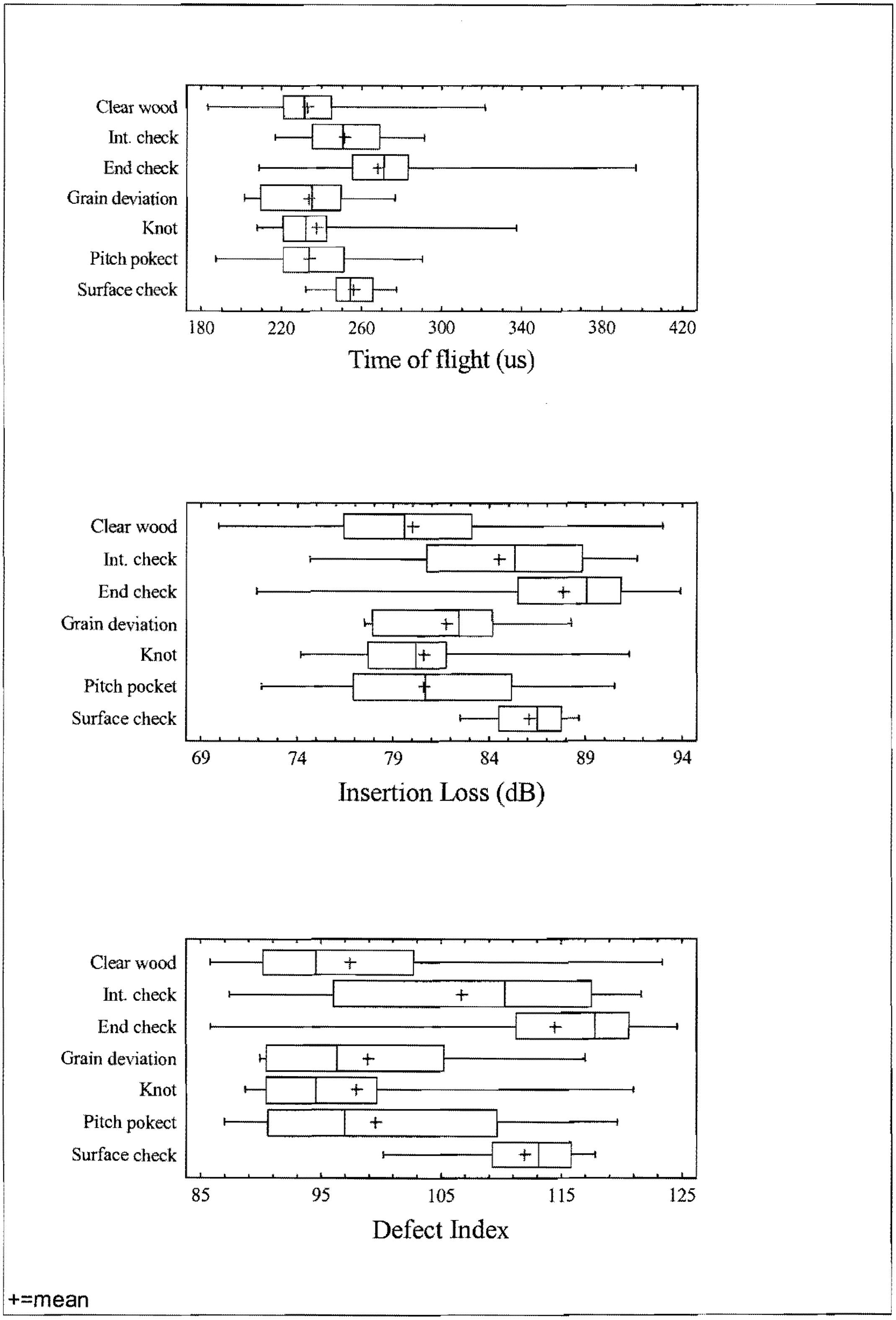


Figure 13. Distribution of the parameters values for each visual inspection group.

Table 7. Contingency table of number of occurrences of internal checks based on visual examination classified according to thresholds set at the parameter mean for clear wood.

	Visual inspection	
Parameter	Clear wood	Internal checks
Time of flight		
≤ 233.1 μs (absent)	11,190	78
> 233.1 μs (present)	9,415	303
Pulse duration		
≤ 89.0 μs (absent)	14,791	144
> 89.0 μs (present)	5,814	237
Insertion loss		
≤ 79.9 dB (absent)	10,967	80
> 79.9 dB (present)	9638	301

Table 8. Contingency table of number of occurrences of other defects based on visual examination classified according to thresholds set at the parameter mean for clear wood.

	Visual inspection	
Parameter	Clear wood	Other defects
Time of flight		
≤ 233.1 μs (absent)	11,190	258
> 233.1 μs (present)	9,415	1,135
Pulse duration		
≤ 89.0 μs (absent)	14,791	355
> 89.0 μs (present)	5,814	1,038
Insertion loss		
≤ 79.9 dB (absent)	10,967	233
> 79.9 dB (present)	9638	1,160

Table 9 and Table 10 show the conditional probability that the system correctly classifies the absence or presence of defects. The correct prediction of presence of defects was much higher than the correct prediction of absence of defects because of the values selected for the thresholds and the variability in the values of clear wood. This variability causes the parameter values of clear wood to overlap with the parameter values of defective wood making it difficult to choose a threshold that can clearly indicate presence of defects.

The probability that a defect is actually present when its presence is predicted was low, 3 to 4 % for internal checks and 11 to 15 % for other defects. This is because 50 percent of the clear wood falls into the defect category based on threshold selection. However the probability of absence of defects when predicted was very high, 98 to 99% due to the high proportion of clear wood in the samples.

Table 9. Conditional probability of prediction of internal checks (%).

	Time of flight	Pulse duration	Insertion loss
Given that the parameter values predict absence of defects, internal checks are actually absent	99	99	99
Given the actual presence of clear wood the parameter value predict absence	54	72	53
Given that the parameter values predict presence of defects, internal checks are actually present	3	4	3
Given the actual presence of internal checks the parameter values predict defects	79	62	79

Figure 14 shows the cumulative distributions of different visual inspection groups for wave travel time, insertion loss, and defect index. Taking the mean parameter value for clear wood as the threshold in the insertion loss graph it can be observed that about 80% of the internal check sample points are above that threshold but they overlap with 60% of the clear wood sample points. This overlap of the cumulative distributions prevents the accurate prediction of defects.

For the method to be successful, the cumulative distribution for clear wood would need to be shifted to the left so that it approached 100 percent before distributions for the defects began to rise from zero.

Table 10. Conditional probability of prediction of other defects (%).

	Time of flight	Pulse duration	Insertion loss
Given that the parameter values predict absence of defects, other defects are actually absent	98	98	98
Given the actual presence of clear wood the parameter value predict absence	54	72	53
Given that the parameter values predict presence of defects, internal checks are actually present	11	15	11
Given the actual presence of other defects the parameter values predict defects	81	74	83

Other defects= surface checks, end checks, knots, pith pockets, grain deviation.

5.8- Relationship between variability in signal and wood parameters

There appeared to be no relationship between the density (p-value = 0.23) or ring angle (p-value = 0.40) and the variability in the signal along the length of a board. Nevertheless, the signal patterns were repeatable, that is that if a board exhibited high variability on one pass, a second pass showed similar results. In addition, the major peaks and valleys tended to be repeatable.

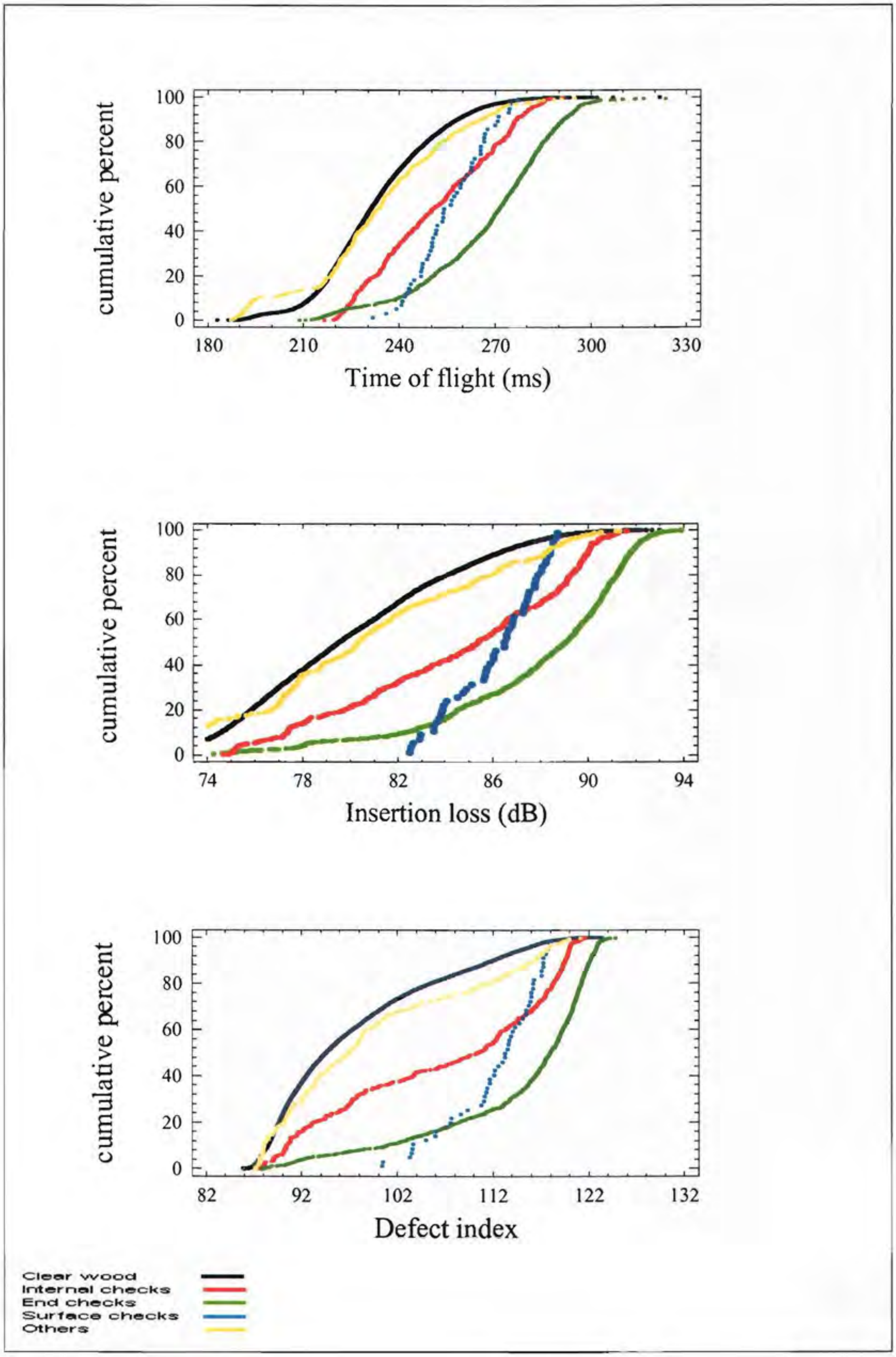


Figure 14. Cumulative frequency of visual inspection groups.

The cause for this was not determined and could not be attributed to anything measured in this study.

It is possible that the coupling of the transducer to the wood varies from piece to piece due to surface characteristics left on the board due to sawing. For example, different machine centers at the sawmill might leave a different pattern of saw marks on the board and affect coupling. However, visual examination of the boards did not reveal any differences in surface characteristics among the groups that would support this hypothesis. It's also possible that some microscopic features within the wood affect the signal transmission. In future work it might be possible to induce microscopic defects by putting the wood in stress beyond its elastic limit (to simulate bending in the tree or at the mill), dynamically stressing the wood (to simulate going over certain pieces of mill equipment), or to age green wood (to allow microbial action at the cellular level).

6- CONCLUSIONS

The selection of a frequency in the range of 120 to 200 kHz did not appear to impact the results except that greater attenuation occurred at the higher frequency.

The use of rolling transducers and the through transmission ultrasonic technique created reproducible results for attenuation, pulse duration, and velocity, particularly when the same feed direction and orientation for the board were used relative to the machine (correlation coefficient of 0.92). When the board orientation was changed, the correlation coefficient was reduced to 0.69 to 0.85, but the technique was still generally reproducible.

End checks are easily detected by the technique and a producer might be able to accurately determine how much end trim is required to obtain clear wood. This would reduce the labor required to visually inspect and trim several times to remove checked ends.

Experimentally, the slicing method of visual inspection was easier to apply than resawing or crosscutting.

While there are statistical significant differences between clear wood and internal, surface, and end checks, it would be difficult to separate these from clear wood in practice because of the overlap in the distributions of the ultrasonic parameters. Clear wood could not be separated from small tight knots or pith pockets. Grain deviations appeared to have no effect on the acoustic transmission.

Even though the ultrasonic technique correctly classifies internal defects about 79% of the time and other defects about 81%, it misses about 20 % of the defects. In addition, approximately 50% of the clear wood would be rejected. If the threshold were adjusted to accept more clear wood, additional defects would pass undetected. There is so much variability that it is difficult to establish thresholds to predict presence of defects.

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