A CRITICAL-ANGLE ULTRASONIC TECHNIQUE FOR THE INSPECTION OF WOOD PARALLEL-TO-GRAIN

James R. Dickens

Graduate Research Assistant
Department of Mechanical Engineering

Donald A. Bender

Professor
Department of Agricultural Engineering

and

Don E. Bray

Associate Professor
Department of Mechanical Engineering

Texas A&M University
College Station, TX 77843

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ABSTRACT

The objective of this paper is to present a critically refracted longitudinal wave (L_{CR}) technique that allows localized ultrasonic inspection of wood parallel-to-grain by accessing only a single side of the material. The L_{CR} technique has been widely applied to other materials, but not to wood. The chief advantage of the L_{CR} technique is that ultrasonic waves can be transmitted through wood at frequencies much higher than previously possible (up to 1.5 MHz), leading to potential gains in sensitivity over lower frequency methods.

The L_{CR} technique was verified using southern pine lumber. Transducer beam characteristics were examined and the influence of growth ring angle was observed. Ultrasonic wave energy was found to travel near to the inspection surface. Further, localized growth ring angle was significantly correlated to signal amplitude and frequency.

Keywords: Critically refracted longitudinal waves, beam profile, growth ring angle.

INTRODUCTION

Vibration-based methods for nondestructive evaluation (NDE) of wood materials have been studied for nearly 40 years. Early work in this field was centered around measuring the velocity of acoustic waves (Lee 1958), determining factors that affect vibrational response (James 1961), and developing the theoretical and practical relations between vibrational properties (e.g., acoustic velocity and energy dissipation) and mechanical properties (modulus of elasticity) (James 1964; Pellerin 1965; Galligan and Courteau 1965). More recently, vibrational methods have expanded to include a variety of sonic and ultrasonic methods. For most engineering materials, ultrasonic methods employ frequencies in the 2–20 MHz range. Due to attenuation, which can be as high as several hundred dB/m, wood materials require lower frequencies, almost exclusively below 1 MHz (Schniewind 1989). Ultrasonic methods encompass a number of related techniques (McDonald 1978, 1979; Falk et al. 1990; Ross and Pellerin 1991). These techniques include (but are not limited to) impact-echo, acoustic emission, through-transmission, and acousto-ultrasonics.

One of the specialized applications of ultra-

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sonic testing uses longitudinal waves that are refracted at an angle of 90° (parallel to the inspection surface). These critically refracted, or L_{CR}, waves have been used in a variety of non-wood material applications, including detection of near-surface defects (Smith 1987; Razygraev and Ermolov 1981; Azemoto and Tsuge 1991), stress evaluation (Egle and Bray 1979; Bray et al. 1989; Srinivasan et al. 1991; Shaikh 1992; Szelazek 1992), assessment of elastic properties (Pilarski and Rose 1989), and material texture studies (Najm and Bray 1986). Advantages of L_{CR} waves include the ability to reliably detect near-surface defects and insensitivity to surface roughness. L_{CR} waves are particularly well suited to the inspection of plate materials, where access is often restricted to a single surface of the component.

Ultrasonic inspection using L_{CR} waves appears ideally suited to wood because it allows inspection parallel-to-grain without the need to access the end grain. A review of the literature reveals that Gerhards (1978) reported the use of a wooden angle coupler as part of a study comparing instruments used for measuring pulse transit times in pine. Logan (1980) patented a method for inspecting veneer using refracted stress waves. Szabo (1978) suggested oblique coupling as an improvement over the surface-transmission method. Biernacki and Beall (1993) recognized that wave energy has the tendency to refract in the direction of the grain. Bucur and Rocaboy (1988) used the principle of mode conversion to excite surface waves by cutting the edge of their test block at a 45° angle, and later (Bucur 1992) used a 45° wedge to receive surface waves. Of these, Gerhards (1978) and Logan (1980) are the only ones who propagated longitudinal waves essentially parallel-to-the-grain direction, and apparently their work did not fully reveal the potential benefits of the refraction technique. The use of high frequency (greater than 1 MHz), critically refracted longitudinal (L_{CR}) waves in wood materials has not been reported in the research literature.

Critical-angle ultrasonic inspection provides an opportunity to inspect wood parallel-to-grain by access to the side grain of the wood. The research described herein demonstrates the feasibility of using ultrasound at a frequency of 1.25 MHz to inspect dimension lumber. This may lead to improved sensitivity to localized material properties. Furthermore, the L_{CR} technique holds considerable promise for the evaluation of products such as finger-jointed lumber and particleboard.

The objective of this research was to develop an L_{CR} technique for wood in order to overcome some of the limitations related to wave frequency and signal attenuation. A custom pitch-catch transducer was constructed, and its performance was evaluated using eight samples of southern pine lumber. Profiles of the beam energy were determined using semicircular wedges of lumber. Beam penetration depth and growth ring effects were studied using notched samples of lumber.

THEORETICAL BACKGROUND

Snell's law is used to describe the relationship between incident and refracted waves at the boundary between two materials (Bray and Stanley 1989). The simplest form of the relation is for an interface between two homogeneous, isotropic solids. Longitudinal wave velocities are invariant under the conditions of isotropy, and hence the angle of refraction can be determined from knowledge of the incident angle:

$$\theta_{\text{refracted}} = \sin^{-1}\left[\frac{C_{\text{refracted}}}{C_{\text{incident}}}\sin\theta_{\text{incident}}\right] \quad (1)$$

L_{CR} waves occur when the angle of incidence is equal to the first critical angle, thus resulting in a refracted wave traveling parallel to the interface.

In anisotropic materials, the relation between angle of incidence and angle of refraction requires the relation between wave speed and direction of propagation to be known (Rose and Deska 1974). For unidirectional (transversely isotropic) fiber composites, an elliptical velocity profile provides a good approximation:

$$C_{refracted} = \sqrt{\frac{C^2_{parallel} C^2_{transverse}}{C^2_{parallel} \sin^2\theta + C^2_{transverse} \cos^2\theta}} \quad (2)$$

The velocities $C_{parallel}$ and $C_{transverse}$ refer to velocities measured parallel and transverse to the fiber direction, respectively. The velocity $C_{refracted}$ varies with the angle of refraction $\theta_{refraction}$ (90° − θ). In a transversely isotropic solid, the system of equations describing Snell's law can be solved simultaneously to find the velocity and refraction angle for both the phase and group components of the refracted wave for an arbitrary angle of incidence. Usually the phase and group components differ both in direction and velocity, which requires a set of at least four equations to solve for the unknowns. However, at the first critical angle, group and phase components of the refracted wave are coincident. All that remains is one unknown (incident angle), for which the simplest form of Snell's law (Eq. 1) can be applied.

Wood is similar to a unidirectional fiber composite both structurally and elastically. Tracheids are analogous to thin carbon fibers and lignin is analogous to an epoxy matrix. While fiber composites have stronger elastic directionality than wood, in both cases the high stiffness direction is parallel to the "fiber" direction. In wood, elastic stiffness is 10 to 20 times greater in the fiber direction than in the transverse direction (USDA 1990). Hence the properties parallel-to-grain tend to dominate overall wood behavior. Since the grain direction in wood is analogous to the fiber direction in composites, and the desired angle of refraction (90°) coincides with the grain direction, Snell's law (Eq. 1) can be used to find the incident angle required to excite an L_{CR} wave in wood using an average value of wave speed measured parallel to the grain direction.

One of the significant effects of elastic anisotropy on wave propagation is that the energy flux vector tends to align with the direction of highest stiffness almost regardless of the original direction of the wave energy. The highest velocity and lowest attenuation are observed in the highest stiffness direction, and hence it appears to present the "path of least resistance" for the wave energy (Kline 1988; Pilarski and Rose 1989; Wu and Ho 1990). Research on austenitic (transversely isotropic) stainless steel weldments has shown that angle of incidence has a greater effect on beam divergence than on the angle of refraction (Hudgell and Seed 1980; Tomlinson et al. 1980; Silk 1981). Furthermore, it has also been shown that beam divergence is minimized when the angle of refraction coincides with the highest stiffness direction. Thus, elastic directionality has a focusing effect on the wave energy. These observations suggest that critically refracted waves should be easily excited in wood and that angle of refraction will be relatively insensitive to the typical wave speed variations encountered in wood materials. However, wave speed variations are likely to cause changes in the beam divergence where "slow" wood would indicate greater beam spreading than "fast" wood.

The Hankinson formula is a well-known equation of wood mechanics that was developed around 1921 to curve-fit a set of empirical data (Kim 1986). This equation is used to describe the angular dependence of wood properties (i.e., the variation of a given property with respect to the grain direction). The form of the equation is:

$$N = \frac{PQ}{P \sin^n\theta + Q \cos^n\theta} \quad (3)$$

The property P is measured parallel to the grain, while the property Q is measured transverse to the grain. Thus the property N at some angle-to-grain θ can be found with an appropriate fitting parameter n (usually 1.5–2.0 for elastic properties). While the conventional uses of this formula include determining tensile strength, compression strength, elastic modulus, and toughness (USDA 1990), more recently the equation has been used for studies of wave speed in wood (Armstrong et al. 1991; Dickens 1996) where a close fit of the empirical data was achieved. In a side-by-side comparison of the elliptical equation of Rose and Deska (Eq. 2) and the Hankinson formula (Eq. 3), a similarity in form is observed. Furthermore, nearly identical numerical results can be achieved between Eq. (2) and Eq. (3) when the Hankinson fitting parameter is about 1.65. Because of this similarity, it appears that using the Hankinson formula is tantamount to making an assumption of transversely isotropic elastic symmetry in wood. As an indication of its utility, the Hankinson formula has been widely applied to wood properties for some 75 years.

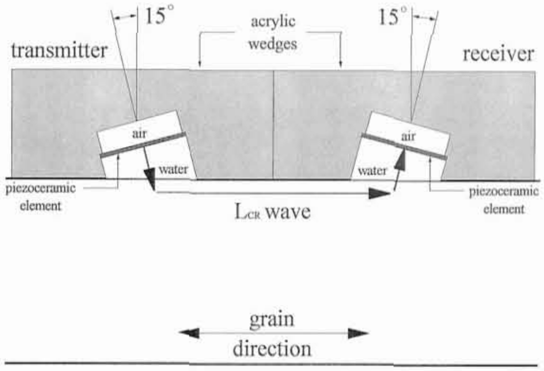

FIG. 1. Pitch-catch transducer arrangement for ultrasonic inspection of pine using L_{CR} waves.

EXPERIMENTAL METHODS

Wave speed studies

A representative measure of wave speed was required in order to find the first critical angle for southern pine. Six individual samples of 2 × 6 dimension lumber were selected and cut to a length of approximately 100 mm. The dimensions and weight of each specimen were recorded. Using a pair of commercial broadband transducers (1.0 MHz nominal frequency, 12.7-mm diameter), wave speed measurements were recorded parallel-to-the-grain. The measurements showed good repeatability, with the coefficient of variation generally less than 4%. The wave speed values observed in this study were somewhat higher than those observed in other recent studies of southern pine (Han 1993; Bethi 1994), probably due to the higher propagation frequency and an end-grain-to-end-grain measurement technique. Wave speeds of up to 6,000 m/sec were observed parallel-to-grain.

The feasibility of propagating critically refracted waves in wood was studied using a set of L_{CR} transducers previously designed for steel. The transducers consisted of a pair of clear acrylic wedges having a 1.0-MHz piezoceramic element (air-backed, narrowband) mounted at an angle of 28° from the vertical. Use of these transducers on wood was possible because the wave speed parallel-to-grain in southern pine is almost identical to the wave speed in steel (near 5,900 m/sec). The 1.0-MHz transducers easily propagated a signal more than 75 mm. Perhaps more significantly, the peak frequency of the received signal remained at the 1.0-MHz nominal frequency of the sending transducer. Using a pair of commercial 2.25-MHz transducers and a similar set of acrylic wedges, the received signal frequency was as high as 1.5 MHz along a 90-mm travel path. This study appears to be the first in which frequencies well in excess of 1.0 MHz have been propagated parallel-to-grain by accessing only the side grain. Inspection at these frequencies leads to the possibility of greater sensitivity to localized material properties such as adhesive bond quality in reconstituted wood products.

Design of a pitch-catch transducer

The following parameters were evaluated during the conceptual development of a transducer for inspecting wood. A brief explanation of the various parameters is provided. Figure 1 shows a schematic of the assembled transducers.

Frequency, bandwidth, and size.—Based on the results of the feasibility study, a relatively high frequency was selected (1.25 MHz). In addition, a narrowband signal was desired in order to maximize the wave energy near the excitation frequency of the transducer. Therefore the piezoceramic crystals were air-backed. An element size of 25.4-mm diameter was chosen.

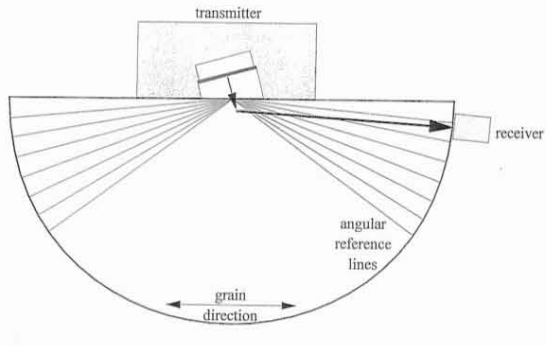

FIG. 2. Beam profile setup.

Coupling.—To reduce variability often associated with solid or gel-type couplants, a water-coupled arrangement was employed. The chief advantage of water coupling was to provide intimate contact with the wood surface without the need for large coupling forces. The coupling layer consisted of an enclosed water cavity between the face of the piezoceramic crystal and the inspection surface. A rubber O-ring seal prevented leakage, and the cavity was filled with a gravity-fed water supply. Using water, a relatively shallow angle of incidence was required. Further, water provided good acoustic impedance matching with the wood surface. Wetting area was limited to the small contact surface beneath the transducer.

Wedge material.—A clear acrylic (polymethylmethacrylate, PMMA) was selected as the wedge material since it is readily available, inexpensive, and easy to machine and assemble. The transparent PMMA allows for accurate positioning of the transducers over the inspection site. In addition, the water cavities can be checked to ensure that all air bubbles have escaped.

Configuration and spacing.—A dual-transducer, pitch-catch configuration was selected to perform localized inspection along a single surface of the lumber. Sending and receiving transducers were constructed identically. The piezoceramic crystals were mounted in PMMA wedges fastened together at a fixed spacing of 76.2 mm (distance between beam entry point and exit point).

Incident angle.—Under ideal circumstances, the angle of incidence would be chosen based on prior knowledge of a relatively constant material wave speed. However, parallel-grain wave speed typically varies by several hundred meters per second within a given species of wood. A design wave speed of 5,700 m/sec was chosen since it represented an average of the measured wave speeds. The water-couplant wave speed was assumed to be 1,480 m/sec (corresponding to a temperature of 20°C). Applying Snell's law (Eq. 1), an incident angle of 15° was selected.

Transducer beam profile evaluation blocks

Two evaluation blocks were machined from samples of clear southern pine 2 × 6 dimension lumber (one flatsawn sample and one quartersawn sample). The blocks were cut edgewise in a semicircular pattern having a radius of 100 mm. These blocks were used to study the profile (radiation pattern) of the L_{CR} transducers. Radial lines were drawn on each block at 5° intervals. The blocks were subsequently treated with a penetrating water sealer to minimize any attenuation effects of material property changes caused by repeated wetting. Block A, which was cut from flatsawn wood, had growth rings oriented perpendicular to the inspection surface (growth ring angle, or GRA, of 90°), while Block B, which was cut from quartersawn wood, had growth rings oriented parallel to the inspection surface (GRA of 0°).

To perform the test, one of the L_{CR} transducers was placed in the center of the narrow face of the block as a sending unit, while a commercial transducer (1.0 MHz nominal frequency, 12.7-mm diameter) was used along the curved edge to receive the signals (Fig. 2). With the sending transducer stationary, the receiving transducer was moved along the curved surface corresponding to the radiation direction of the sender. A water-based gel couplant was used for the receiving transducer, while the sending transducer was water-coupled as originally designed. Signals were saved on disk for each 5° increment. Both L_{CR} transducers

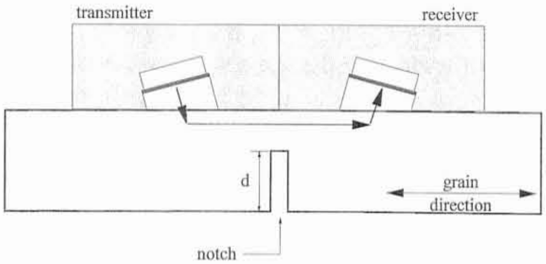

FIG. 3. Beam depth-of-penetration setup.

were tested using each of the two semicircular blocks.

Beam depth-of-penetration studies

A second means of assessing beam radiation pattern was devised for comparison. This consisted of partially sawing a notch through clear sections of wood (opposite the inspection surface) and looking for changes in the received signal resulting from the presence of the notch (Fig. 3). Six sections of clear southern pine 2 × 6 dimension lumber were selected ranging in length from 0.5 to 0.75 m. The wide face of the boards was marked with a grid for positioning the pitch-catch transducer pair. Three approximately equally spaced locations were marked in the width direction, and the growth ring angle at each location was measured by reference to the end grain. At the midpoint of the transducer position, a saw line was marked on the opposite face of the board. All samples were treated with a penetrating water sealer.

Ultrasonic readings were recorded on all six specimens for a total of 30 observations. Signal characteristics of particular interest included amplitude and peak frequency. Then a shallow, uniform cut was made along the saw line of each piece. The depth of the cut was measured using a digital caliper. Then ultrasonic tests were repeated. Next, a slightly deeper cut was made on each piece. The saw cutting and ultrasonic testing were repeated a total of five times, to a point where the boards had been nearly sawn through. The thickness of the remaining section was less than 5 mm after the fifth saw cut.

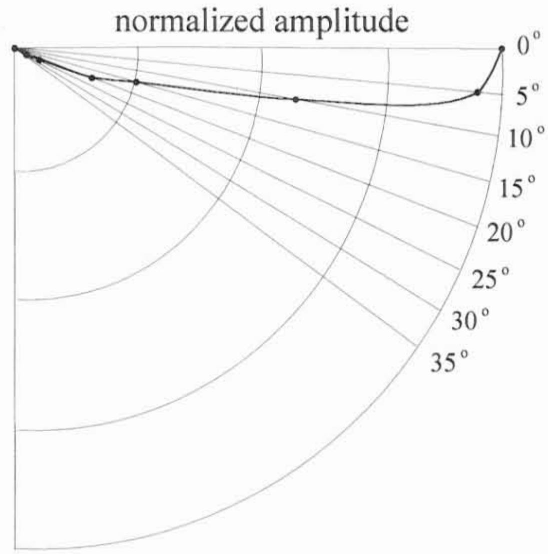

FIG. 4. Profile of critically-refracted longitudinal wave in Block A (GRA = 90°). Wood is flatsawn with respect to the wide face.

RESULTS AND DISCUSSION

Transducer beam profile

Two representative beam profiles are shown in Figs. 4 and 5. These polar plots show nor-

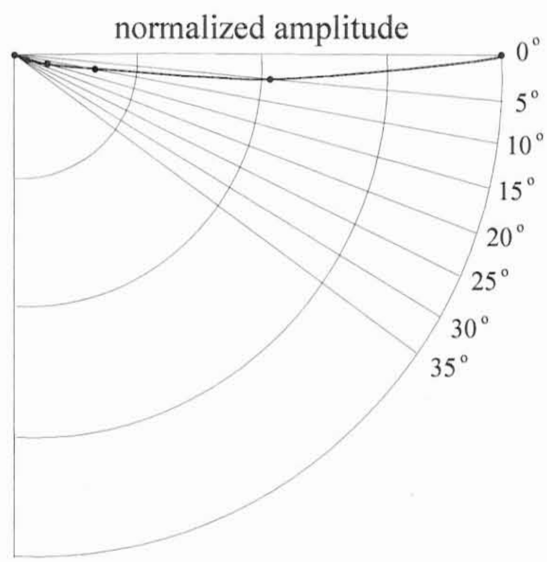

FIG. 5. Profile of critically refracted longitudinal wave in Block B (GRA = 0°). Wood is quartersawn with respect to the wide face.

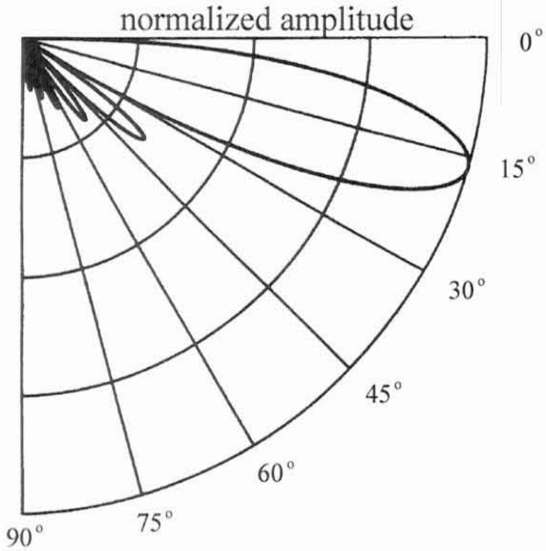

FIG. 6. Profile of a critically refracted longitudinal wave in an isotropic medium. Adapted from Langenberg et al. (1990). Used with permission.

malized signal amplitude as a function of angle from the horizontal (on a linear scale). No measurable signals were observed beyond an angle of 35°. Block A (GRA = 90°, Fig. 4) shows that peak amplitude occurs near the surface and rapidly diminishes beyond an angle of 15°. Block B (GRA = 0°, Fig. 5) shows similar results except that signal strength diminishes even more rapidly. Profiles of L_{CR} waves in isotropic materials are similar (Fig. 6), except that the pressure maximum occurs about 15° below the surface (Langenberg et al. 1990; Junghans and Bray 1991). The most significant observation in the beam profile evaluation was that at an incident angle of 15°, a majority of the wave energy was directed parallel to the inspection surface, which corresponds to the grain direction in the wood. This indicates that the L_{CR} transducer excited a refracted longitudinal wave in precisely the manner intended.

By considering the difference in wave speed between the two blocks, an explanation for the differing profiles is possible. Recall that the L_{CR} transducer was designed with an assumed wave speed of 5,700 m/sec parallel-to-grain. In Block A, the actual parallel-grain wave speed was 5,190 m/sec, or 510 m/sec (9%) lower than the design wave speed. Block B, on the other hand, had an actual parallel-grain wave speed of 5,971 m/sec, or 271 m/sec (5%) higher than the design wave speed. As indicated earlier in the paper, angle of refraction in unidirectional composites is robust with respect to changes in wave speed, but beam divergence angle is likely to be affected. For example, the 15° incident angle is 1.6° shallower than the optimal value for Block A, resulting in greater spread of the wave energy. On the other hand, the 15° incident angle is 0.7° steeper than the optimal value for Block B, resulting in greater concentration of wave energy near the surface of the wood. In addition to having a narrower profile, Block B had higher absolute signal amplitudes relative to Block A, which suggests a redistribution of the beam energy closer to the inspection surface.

Beam depth-of-penetration

Growth ring angle was significantly correlated to signal amplitude ($R = -0.56$). Hence, higher growth ring angles were associated with lower signal amplitudes and vice versa. From this relation it appears that growth rings have a waveguide effect where lower growth ring angles tend to trap the signal energy close to the surface due to the distinct layers of earlywood and latewood within the growth rings.

Growth ring angle was significantly correlated to signal frequency ($R = -0.26$). While the relation was slight, higher growth ring angles were nevertheless associated with lower signal frequency and vice versa. In particular, signal components greater than 1.2 MHz were present only for growth ring angles less than 60°. At steeper growth ring angles, only signal components less than 600 kHz were present. This suggests a scattering effect of high frequency signal components due to the growth ring orientation.

Notch depth was not significantly correlated to amplitude or frequency. In short, scatter plots and regression analysis showed that increasing the notch depth was not related to changes in the characteristics of the received ultrasonic signals. This suggests that the notches could not be sawn deeply enough to influence the flow of wave energy. Since the remaining wood section was less than 5 mm in thickness, the earliest arriving wave energy must have been traveling in the grain direction parallel to, and just beneath, the surface of the testpiece. Hence, notch depth data and beam profile data lead to the same conclusion.

Coupling method

The water-coupling method utilized for this study provided consistent results across several repetitions. While this type of approach is useful for a preliminary research study, in-process materials assessment techniques using water coupling may not always be practical. Transducers mounted inside roller wheels may provide a workable alternative, and the angle of incidence can still be tailored to the inspection requirements.

SUMMARY AND CONCLUSIONS

The critical-angle (L_{CR}) ultrasonic technique represents a significant breakthrough for nondestructive evaluation of wood materials. With this type of method, inspections can be performed over localized areas from the side grain of the wood. Additionally, attenuation effects can be greatly reduced by utilizing a travel path oriented parallel-to-grain. Higher inspection frequencies are made possible, which in turn gives rise to improved sensitivity to material properties.

The L_{CR} technique has proven feasible for southern pine and is under further study. Lumber test specimens showed that a significant amount of wave energy was refracted along the grain direction and traveled very near to the inspection surface, even for specimens with velocities higher and lower than the design velocity. Received signal frequencies of up to 1.5 MHz were achieved along a 90-mm travel path. Localized growth ring angle appeared to have a significant effect on signal amplitude and frequency, where increasing growth ring angle was associated with a decrease in both signal amplitude and frequency. Further development of the L_{CR} technique described in this paper may prove beneficial for the characterization of both solid-sawn and reconstituted wood materials.

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