DEVELOPMENT OF AN ACOUSTO-ULTRASONIC SCANNING SYSTEM FOR NONDESTRUCTIVE EVALUATION OF WOOD AND WOOD LAMINATES

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ABSTRACT

An acousto-ultrasonic (AU) scanning system was developed and optimized for wood products. It was found that AU probe alignment, coupling pressure, and stabilization time affect the repeatability of AU readings. After optimization of these factors, the error in AU reading (RMS) was negligible. AU transmission through solid wood also showed a relationship of acoustic attenuation to wood anisotropy. A calculated modulus of elasticity in the direction of wave propagation correlated with wave attenuation characteristics in the TR and LR planes. For wave propagation in the TR plane, the greatest attenuation was observed at a growth ring angle (GRA) of about 45°, corresponding to the lowest modulus of elasticity, which is in this plane. The effect of wood anisotropy (GRA) was found to be a major problem for evaluation of laminated wood, since the received signal was strongly affected by wood properties. Consequently, the effect of anisotropy and natural variability of wood will be the major limiting factor of any acoustic NDE technique applied to many wood products.

Keywords: Acousto-ultrasonics, adhesive bond, orthotropy, modulus of elasticity, growth ring angle.

INTRODUCTION

Acousto-ultrasonics (AU) was originally developed as a means to assess flaw distribution and associated changes of the mechanical properties of fiber-reinforced composites (Vary and Lark 1979). Recent research has shown that AU can predict damage developed in composites (Duke and Kiernan 1988; Mitchell 1988), quality of adhesively bonded joints (Fahr et al. 1988), and material anisotropy (Kiernan and Duke 1988). Because of the similarity between fiber-reinforced composites and wood, this method has also been applied to wood products, including AU characterization of wood hardboard (dos Reis and McFarland 1986), detection of decayed wood (Patton-Mallory et al. 1987; Patton-Mallory and

DeGroot 1989), and evaluation of adhesive bonds (Beall and Biernacki 1992a, b; Beall 1991; Beall 1990; dos Reis et al. 1990a, b). The only commercial application of AU to wood products relates to evaluation of particleboard quality with AU through-transmission (Green 1990).

Acousto-ultrasonics began as a combination of conventional ultrasonic testing (UT) and acoustic emission (AE). Similarly to ultrasonic through-transmission, in the AU method a stress wave is injected into a material and the response is captured at another point of the specimen. However, the received signal is processed using methods similar to those used in AE, measuring various waveform parameters rather than reflections from discontinuities, as

in UT. Efficiency of wave propagation is correlated with the physical properties of the material. Lower wave attenuation is associated with greater fracture resistance, absence of material defects, and higher overall strength. Unlike well-defined wave paths, as in UT, the received AU signal is a result of multiple reflections, wave interactions, and mode changes (Vary 1989).

Various means have been used to measure the transmitted wave energy. In an early AU approach, signal energy was assessed using the "stress wave factor" (SWF), defined as a product of the pulse repetition rate, reset time of the counter, and number of positive slope crossings of the waveform over a preselected threshold (Vary and Lark 1979). Since SWF depends on an arbitrarily established threshold, other means of measuring wave energy have replaced the SWF. For example, RMS (root mean square) voltage and maximum voltage peak are measurements independent of threshold level, and therefore give a more precise estimation of the signal energy (Vary 1989). Increased availability and reduced costs of computers and A/D converters have permitted precise digitization of the signals and definition of many other features in the time and frequency domains, such as the area within time and frequency intervals, centroids, moments, peaks of frequency, and others (Vary 1989; Biernacki 1991).

Despite the sensitivity, versatility, and simplicity of AU, this method suffers from poor repeatability due to material variability, coupling conditions, transducer misalignment, and other set-up related factors. Although some of these variables can be controlled in the laboratory, the commercial application of AU, even with homogeneous materials, is still a challenge. Implementation of AU to wood products is even more difficult because of anatomical variability (grain and growth ring angles), defects (knots and discontinuities), surface roughness, and other inhomogeneities.

Recent studies on the mechanisms of wave propagation in anisotropic materials (primarily fiber-reinforced composites) show a dependence of the wave energy flux on the elastic properties of material in different directions. For example, with a 4-ply [0,0,0,0] fiber-reinforced laminate, it was shown that the wave energy transmission vs. angle to fiber direction (azimuthal angle) exhibited the same behavior as the corresponding modulus of elasticity (Kiernan and Duke 1990). Also, finite element modeling gave an explanation of how a wave propagates in an orthotropic material in various directions with respect to the fiber orientation (Lord et al. 1988). Data presented in the latter paper illustrated a focusing effect of the fiber orientation for wave propagation along fibers and a defocusing effect for waves across the fiber direction (azimuthal angle = 90°). An even more interesting pattern resulted for an angle to the fiber direction of 45°, in which case the wavefront refracted in the fiber direction. Skewing effects of wave propagation have also been observed experimentally, in which the wave energy-flux vector deviated from the normal direction in thick anisotropic materials, causing problems in detection of a crack (Green 1991). On the basis of the above data, one may assume that an acoustic wave preferably follows (refracts in) the direction of greater stiffness.

The objective of this paper was to develop and optimize an AU scanning system for assessing the properties of wood products. First, before material properties (wood defects, voids, decay) could be assessed, the AU system variables were identified and their effects minimized. Following this, the effect of material (wood) on stress wave propagation characteristics was evaluated. For this study, growth ring angle (the acute angle between the nominal direction of wave propagation and the tangential plane) was selected as the key wood variable. Results are presented in two sections: development of the AU system to maximize repeatability, and determination of the effect of anisotropy of wood on wave propagation.

THEORETICAL CONSIDERATIONS

Understanding wave propagation in wood requires consideration of continuum and material geometry. Wood may be considered as

a locally orthotropic solid with nine independent elastic constants (Bodig and Jayne 1982). Stress-strain relations in Cartesian components can be described by the well-known equation:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl} \qquad (1)$$

where

σ_{ij} = stress components
C_{ijkl} = components of stiffness tensor
ϵ_{kl} = components of the strain.

The following equations relate strain with displacement (u_i)

$$\epsilon_{kl} = (1/2)(u_{k,l} + u_{l,k}) \qquad (2)$$

Finally, the equation of motion (with no body force) is given by

$$\sigma_{ij,j} = \rho u''_i \qquad (3)$$

where ρ is density, and u''_i is second time derivative of displacement.

Combining Eqs. (1), (2), (3) and applicable boundary conditions permits solution of a wave propagation problem for an arbitrary input (Musgrave 1970). However, the stiffness tensor is subject to a transformation

$$C_{mnop} = a_{mi}a_{nj}a_{ok}a_{pl}C'_{ijkl} \qquad (4)$$

where a_{mi}, etc., are components of the transformation tensor, dependent on grain angle and growth ring angle in the location of interest. In general, both the stiffness tensor and density are functions of a position vector. Because of the natural origin of wood, those functions are difficult to assess exactly and can only be approximated. For practical applications of AU to nondestructive evaluation, this means a large variability of the output parameters, which may or may not be offset by a material feature of interest, such as wood decay, weak adhesive bonds, or other defects.

EXPERIMENTAL APPROACH

Materials

The effect of coupling conditions and signal stabilization was tested using three Douglas-
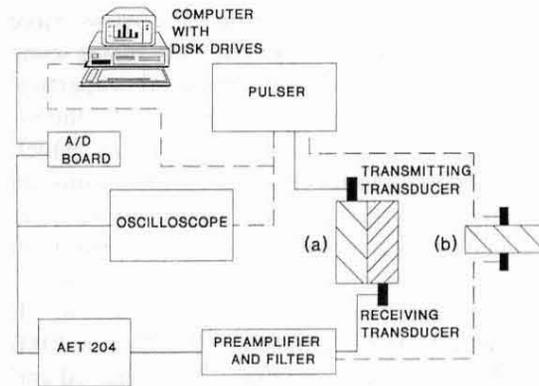

FIG. 1. AU signal flow and instrumentation for specimens in (a) offset through-transmission and (b) through-transmission.

fir 2 by 6's with random GRA. The through-transmission testing mode was used as shown in Fig. 1b.

To study the effect of growth ring angle (GRA) on acoustic wave attenuation, sixty 48-× 140-× 600-mm (last dimension along the grain) Douglas-fir specimens were tested in face-to-face through-transmission (Fig. 1b). The specimen material consisted of five GRA groups: 0, 30, 45, 60, and 90°, with 12 specimens per group. All specimens were equilibrated at a nominal EMC of 12% (RH = 66%, T = 20 C) for six months.

The specimens for the effect of paired laminates were tested in offset through-transmission (Fig. 1a). There were eight assemblies, each a pair of clear Douglas-fir 2 by 6's, bonded using a commercial resorcinol adhesive (Cascophen RS-240MD/Cascoset FM-124D) with random GRA. This configuration has been used to simulate the evaluation of glulam beams (dos Reis et al. 1990a; dos Reis 1989).

Equipment and procedure

Figure 1 shows a signal flowchart, instrumentation, and nominal specimen cross sections for the AU system developed for the project. A high voltage spike pulse created by the pulse generator/pulser (Tektronix TM503) with a repetition rate of 1 kHz was sent to the piezoelectric transmitting transducer (AET, 375 kHz), which transformed the electrical signal

into a mechanical vibration. The stress wave traveled through the material, undergoing some changes in response to the material properties. The transmitted wave was captured by the receiving transducer (AET, 110 kHz), which transformed the mechanical vibration into an electrical signal. The signal from the receiver (actual signal frequency was 100 kHz) was then amplified and filtered in a 140B AET preamplifier (0.650 to 125 kHz band pass, 40 dB gain), and further amplified (10 dB) in a 204B AET unit. Finally, the signal was digitized and stored on a personal computer (PC) hard drive for further analysis.

The piezoelectric transducers were mounted in probe assemblies, which protected the transducer from wear, transmitted the coupling force without loading the transducer, and helped to align the coupling surfaces to the probe and material. The probe consisted of the transducer, a plastic (nylon) waveguide, and a transducer holder. One end of the plastic waveguide was connected to the transducer shoe using a grease ultrasonic couplant (AET SC-6). On the other end of the waveguide, a 25-mm-diameter silicone rubber disc was attached to act as a dry couplant between the probe and the material. Coupling force was transmitted from the transducer holder through a thick (15-mm) soft rubber spring on the waveguide, without loading the transducer. The rubber spring self-aligned the coupling surface to the material.

The testing was fully automated in controlling specimen positioning, probe clamping/unclamping, and signal recording by the PC (Micro-1, an IBM-compatible AT286). The computer was equipped with the following boards:

(a) MSTEP-5, a stepper motor and position encoder control board to position and read precise location of data points (XY-table control),

(b) DACA, a low cost data acquisition and control board to read the analog signal level and control the probe clamping devices (air cylinders),

(c) STR*832, a high sampling rate A/D converter to record the AU signal (time domain waveform).

A computer program, AU-SCAN, was developed to control the testing operation. The system was designed to perform unattended data acquisition on a rectangularly shaped area using through- or same-side transmission in a continuous or stepwise testing mode. The data recorded by AU-SCAN included position of data points in a plane (in the X and Y directions), signal level (RMS voltage), and the complete time-domain waveform.

Automation of the testing operation not only eliminated otherwise laborious manual data acquisition, but also reduced the possibility of human error by accurately controlling testing variables such as probe position and application time. In addition, the successful implementation of the automated AU system suggested means of applying AU in commercial conditions. Additional details of the system have been reported elsewhere (Biernacki 1991).

The next step in processing the data was feature extraction, in which numerical values were obtained from the waveform. For this purpose, a computer program, AU-CALC, was developed to compute various AU signal features (AUSF). AUSF extraction included RMS voltage, transit time, area under the curve, centroid time, centroid frequency, moments, and various other time- and frequency-domain parameters. In addition, AU-CALC permitted time and frequency partitioning, and digital filtering (FIR).

RESULTS AND DISCUSSION

Repeatability of AU measurements

Several hardware-related factors were found that affected repeatability of AU readings. Coupling conditions and AU signal stabilization were investigated and optimized in this study.

Coupling conditions. — Although many ultrasonic techniques use various materials, such as glycerin, silicone grease, and water to couple stress waves from a transducer to a specimen, this is unacceptable for wood because such

agents would penetrate the surface, not only altering the acoustic properties, but also damaging or contaminating the product. For this reason, only dry coupling should be employed, which typically uses an elastomeric material as the couplant. However, the use of elastomerics creates some problems, since signal transmission is affected by coupling conditions, such as coupling pressure, area of contact, and alignment of the surfaces.

A preliminary study of the effect of coupling pressure on AU transmission showed that signal energy output increased with increasing pressure (Fig. 2). This may be explained by reduction of microgaps and other mechanical changes (such as creep) within the coupling interface (wood and couplant surfaces). Since the pressure effect decreased with increasing pressure, loading above or near saturation (pressure above which there was no increase of the signal level) was used to reduce variability and increase the signal to noise ratio.

Another factor affecting repeatability is variable coupling to the wood surface due to earlywood and latewood zones. Because of differences in wood density (and related surface roughness), greater transmission occurs if the AU probe is placed on a latewood vs. and earlywood zone (Biernacki 1991). To reduce this effect (and therefore reduce variability), the area of contact between the AU probe and the material was increased so that more than one growth ring was covered. A coupling area of 490 mm² (25-mm diameter) gave acceptable results.

The last hardware effect investigated was alignment of the coupling surface to the surface of material. It is virtually impossible to align the probe perfectly since most wood products have surface waviness. For an elastomeric couplant, misalignment of both surfaces, although small, may produce large stress gradients since the thin (1.5-mm) flat rubber couplant remains in a lateral strain restraint, which also follows that the normal strain is also zero. Rubber is nearly incompressible, so if strains in two perpendicular directions are zero, the strain in the third direction must also be zero in order to
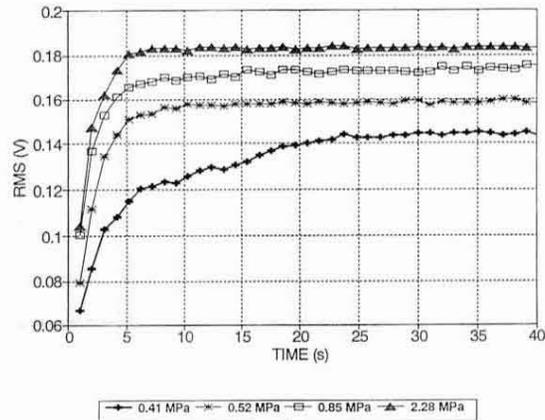

FIG. 2. Stabilization and pressure effect on AU transmission as measured by RMS output.

maintain constant volume. This may produce an uneven stress distribution or even a gap at one edge of the coupling interface, leading to nonuniform wave transmission. As a solution, a flexible AU probe equipped with a thick soft rubber spring was developed. The 15-mm-thick rubber spring provided a deflection much larger than the linear differences related to the misalignment of the probe under the same load, making the stress distribution on the coupling interface more uniform.

Stabilization.—Poor coupling conditions may cause the AU energy output to increase significantly with time (Fig. 2). This behavior is undesirable because it produces variability of sequential AU readings and increases inspection time, which may be significant for in-line commercial applications of AU. The problem was solved in two ways: (a) setting a standard stabilization time for all AU readings and (b) decreasing the time required for stabilization. Figure 3 shows the error in percentage of RMS reading as a function of stabilization time, defined as:

$$\text{Error}(t) = [dV(t)/dt] \times [100/V(t)] \quad (5)$$

where Error(t) is a potential error in reading due to a 1-s increment of stabilization time. As shown in Fig. 3, Error(t) converges to zero for a stabilization time of 10 s, which was selected as a standard time for taking AU read-
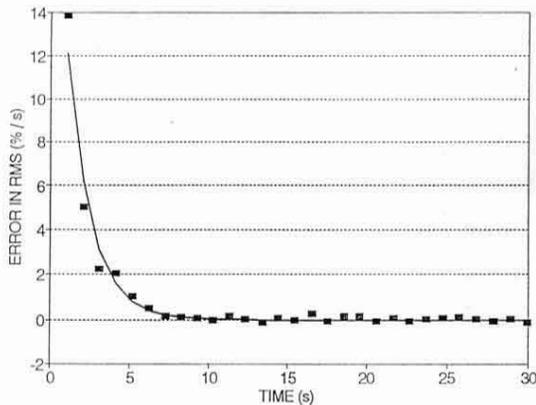
FIG. 3. Potential error in AU readings as affected by stabilization time (2.28 MPa).

FIG. 4. RMS and modulus of elasticity vs. growth ring angle (GRA) for Douglas-fir (0° = tangential direction).

ings (time from clamping to reading). Because the testing was automated, the stabilization time could be accurately controlled (with a tolerance of about 1 ms), which also minimized variability. Stabilization time was reduced by using higher coupling pressure (see Fig. 2) and through some modifications in AU probe construction.

One conclusion of the study of AU hardware-related factors was that the higher the coupling pressure, the better the performance of the system. However, wood hardness may limit the pressure, in that a highly loaded AU probe could damage the surface. This is especially likely if the face of the probe is placed (or partially placed) on the low density earlywood portion of a growth ring. Although marks on the wood surface may not affect mechanical properties, they could significantly decrease the aesthetic value of a wood product. Based on the experimental data, a coupling pressure of 410 kPa (25-mm diameter coupling face under 200 N load) was found to be optimum.

Effect of wood anisotropy on wave propagation

Investigation of the effect of GRA on wave propagation shows a relationship between elastic constants and wave attenuation. Figure 4 shows the AU signal RMS voltage (approximation of signal energy) and the MOE vs GRA. MOE may be calculated from the transformation of the compliance tensor ($S = C^{-1}$) in
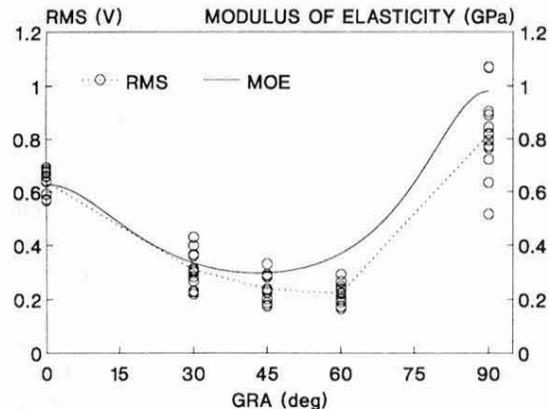
the TR plane. The solution for MOE as a function of GRA (ϕ) gives

$$MOE(\phi) = 1/S_{1111} \qquad (6)$$

and

$$MOE(\phi) = [\cos^4\phi/E_t + (1/G_{tr} - 2v_{rt}/E_r) \\ \times \sin^2\phi \cos^2\phi + \sin^4\phi/E_r]^{-1} (7)$$

where S_{1111} is the component of the compliance tensor after transformation

ϕ = GRA
E_t = MOE in the tangential direction
G_{tr} = modulus of rigidity in the TR plane
v_{rt} = Poisson's ratio
E_r = MOE in the radial direction

The following values for Douglas-fir were used for MOE vs. GRA in Fig. 4:

E_t = 628.4 MPa
G_{tr} = 85.02 MPa
v_{rt} = 0.47
E_r = 981.1 MPa (Bodig and Jayne 1982)

The relationship of AU to modulus of elasticity was also found for the LR plane. Figure 5 shows AU same-side transmission (RMS) vs. the grain angle of a ponderosa pine board (AU data from Lemaster and Dornfeld 1987) and the corresponding MOE, which was calculated using Eq. (7), substituting T, R elastic constants by those for L, R. A linear regression of
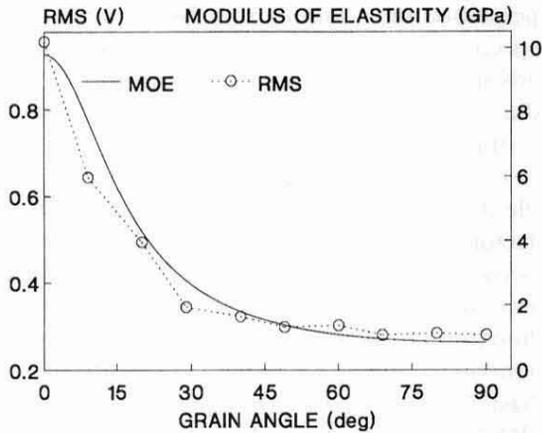
FIG. 5.   RMS and modulus of elasticity vs. grain angle for ponderosa pine (AU RMS data from Lemaster and Dornfeld 1987).
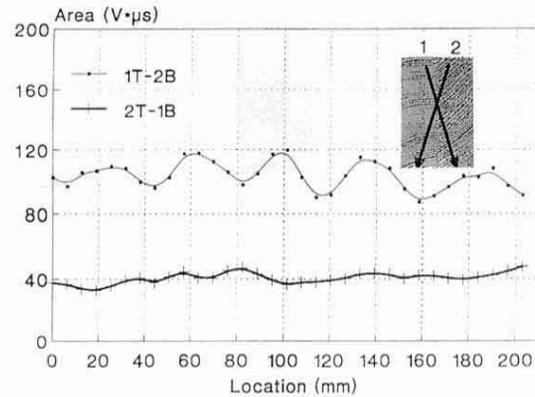

FIG. 6.   Results of AU scan along the grain (starting 50 mm from the end) in offset through-transmission for non-symmetrical laminates showing significant difference between signal levels in two pulsing directions.

MOE vs. RMS gave a close correlation ($R^2 = 0.96$).

Application of the findings from wave propagation in the fiber-reinforced composites to the previously investigated wood system explains the mechanism of wave attenuation in transverse directions (TR plane). For example, with GRA = 0° (tangential direction), the direction of wave propagation corresponds to the greatest modulus in the GRA range of $-45°$ to 45° (wave spread), which would cause wave focusing in this plane. Similarly, a wave would also be focused for GRA = 90° (radial direction). In contrast, for GRA = 45°, a wave defocusing effect (or refraction in both tangential and radial directions) would be expected because the lowest modulus of elasticity is in this plane, which explains the behavior shown in Fig. 4. It is also worth noting that wave dissipation after diffraction was possible because of lack of any boundary in proximity to the wave path (specimen width was sufficient for a wave to dissipate in the direction perpendicular to the wave propagation; see Fig. 1).

Effect of GRA in adhesively bonded material

The results presented in this section describe the significance of wood anisotropy in inspection of adhesively bonded material, such as glulam. Figure 6 gives the rectified area under the time domain waveform (AREA) vs. length for a specimen with nonsymmetrical laminates, showing two pulsing directions, denoted as (a) 1T-2B, transmission from the top of laminate 1 to the bottom of laminate 2, and (b) 2T-1B, from the top of laminate 2 to the bottom of laminate 1. The difference in the received signals can be explained by different angles between wave direction and the growth rings for the two pulsing directions. Specifically, 1T-2B corresponds to GRAs of 80 and 70°, which gives relatively low attenuation (see Fig. 4). In contrast, 2T-1B gives GRA of 50 and 30°, in which the attenuation is the highest (the lowest RMS) in the TR plane. For symmetrical laminations, however, the GRAs are the same in both pulsing directions (1T-2B and 2T-1B), so no significant difference in attenuation should be expected, which is shown in Fig. 7. Expanding on this, since GRA is random in glulam laminates, each bonded laminate would define its own unique reference signal, making it difficult to assess the quality of adhesive bonds, decay, or wood defects. Obviously, this is the major problem for practical application of AU, since the reference value would always be unknown. Inspection of the results obtained on other assemblies confirmed this observation. In addition to variability of the signal level between scanning di-
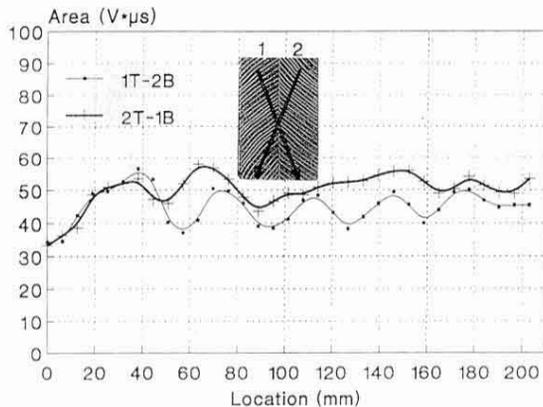
FIG. 7. Results of AU scan along the grain (starting 50 mm from the end) in offset through-transmission for symmetrical laminates showing similar signal levels in two pulsing directions.

rections, there appears to be some variability in patterns along the grain (fluctuation with a period of about 100 mm), but in the same pulsing direction as shown in Fig. 6. Although the reason of this fluctuation is unknown, time domain windowing (partitioning to use only the first 64 μs) appears to reduce this variation (Fig. 8).

CONCLUSIONS

A fully automated AU system was developed for feasibility studies of this technology for various wood products. Automation of the testing operation also reduced human error and
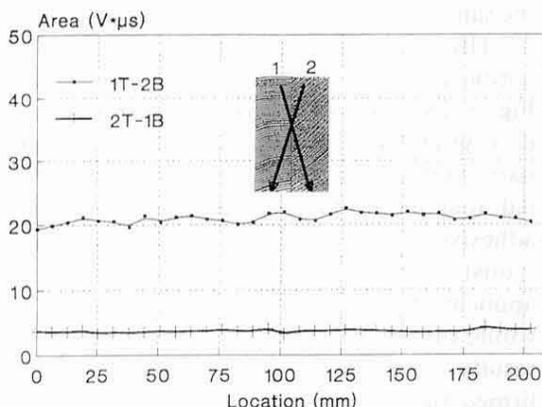

FIG. 8. Reduction of variability by signal partitioning (compare with Fig. 6).

permitted the scanning of a large number of specimens at high resolution. Some significant advances in dry coupling techniques have reduced variability of AU readings in a stepwise testing mode.

For clear wood, the effect of growth ring angle (GRA) on wave propagation is the major factor of the variability in AU transmission perpendicular to the grain. The calculated modulus of elasticity in TR plane (MOE as a function of GRA) and LR plane (MOE as a function of the grain angle) showed the same basic behavior as the AU signal level readings (RMS) in those planes. Similar patterns have been observed and modeled for other anisotropic materials, such as fiber-reinforced composites, which were explained by a skewing effect in the direction of greater MOE (the fiber direction). The results presented in this paper showed that AU can similarly be applied to assess elastic properties of wood.

The significance of these findings has been shown in the application of AU to wood laminate (glulam) evaluation. Because of random orientation of growth rings in the laminates, different attenuation is anticipated for adjacent laminates. This may mask defects, such as weak adhesive bonds. More research is needed in this area in order to develop acceptable predictability of material properties.

REFERENCES

BEALL, F. C. 1990. Use of AE/AU for evaluation of adhesively-bonded wood-base materials. Pages 45–53 *in* Proceedings, Seventh International Symposium on Nondestructive Testing of Wood, Madison, WI.

———. 1991. Nondestructive evaluation of adhesion using acousto-ultrasonics. Pages 97–102 *in* Proceedings, Wood Adhesives 1990, Madison, WI.

———, AND J. M. BIERNACKI. 1992a. An approach to the evaluation of glulam beams through acousto-ultrasonics. Pages 73–88 *in* Proceedings, Eighth International Symposium on Nondestructive Testing of Wood, September 1991, Vancouver, WA.

———, AND ———. 1992b. Detection of adhesion flaws in parallel laminates of lumber using acousto-ultrasonics. *In* Proceedings, Adhesives and Bonded Wood Symposium, November 1991, Seattle, WA (in press).

BIERNACKI, J. M. 1991. Bond quality evaluation of laminated timbers with acousto-ultrasonics. M.S. thesis, University of California at Berkeley, Berkeley, CA. 128 pp.

BODIG, J., AND B. A. JAYNE. 1982. Mechanics of wood and wood composites. Van Nostrand, New York, NY. 712 pp.

DUKE, J. C., AND M. T. KIERNAN. 1988. Predicting damage development in composite materials based on AU evaluation. Pages 191–200 *in* J. C. Duke, Jr., ed. Acousto-ultrasonics: Theory and applications. Plenum Press, NY.

FAHR, A., S. LEE, S. TANARY, AND Y. HADDAD. 1988. Estimation of strength in adhesively bonded steel specimens by acousto-ultrasonic technique. Material Evaluation 47(2):233–240.

GREEN, A. T. 1990. Qualification of particleboards on the mill line. Pages 149–160 *in* H. dos Reis, ed. Nondestructive testing and evaluation in manufacturing and construction. Hemisphere Publishing Co., New York, NY.

GREEN, R. E.. 1991. Ultrasonic waves in anisotropic materials: Past, present and future. 1991 ASNT Fall Conference and Quality Testing Show, September 1991, Boston, MA. Pp. 42–46.

KIERNAN, M. T., AND J. C. DUKE, JR. 1988. Acousto-ultrasonics as a monitor of material anisotropy. Material Evaluation 46(8):1105–1113.

———, AND ———. 1990. A physical model for the acousto-ultrasonic method. NASA Contractor Report 185294. 262 pp.

LEMASTER, R. L., AND D. A. DORNFELD. 1987. Preliminary investigation on the feasibility of using acousto-ultrasonics to measure defects in lumber. J. Acoustic Emission 6(3):157–163.

LORD, W., R. LUDVIG, AND Z. YOU. 1988. Finite element modeling of ultrasonic wave propagation in materials. Pages 1–7 *in* New directions in the nondestructive evaluation of advanced materials, Winter Annual Meeting of Mechanical Engineers, November 1988, Chicago, IL.

MITCHELL, J. R. 1988. Multi-parameter, multi-frequency acousto-ultrasonic for detecting impact damage in com-posite. Pages 311–312 *in* J. C. Duke, Jr., ed. Acousto-ultrasonics: Theory and applications. Plenum Press, New York, NY.

MUSGRAVE, M. J. P. 1970. Crystal acoustics. Holden-Day, San Francisco, CA. 288 pp.

PATTON-MALLORY, M., AND R. C. DE GROOT. 1989. Detecting brown-rot decay in southern yellow pine by acousto-ultrasonics. Pages 29–43 *in* Proceedings, Seventh Symposium of Nondestructive Testing of Wood, Pullman, WA.

———, K. D. ANDERSON, AND R. C. DE GROOT. 1987. An acousto-ultrasonic method for evaluating decayed wood. Pages 167–182 *in* Proceedings, Sixth Symposium of Nondestructive Testing of Wood, Pullman, WA.

DOS REIS, H. L. M. 1989. Non-destructive evaluation of adhesive bond strength in laminated wood beams. British J. Non-Destructive Testing 31(12):675–679.

———, AND D. A. MCFARLAND. 1986. On the acousto-ultrasonic characterization of wood fiber hardboard. J. Acoustic Emission 5(2):67–70.

———, F. C. BEALL, J. V. CARNAHAN, M. J. CHICA, K. A. MILLER, AND V. M. KLICK. 1990a. Nondestructive evaluation/characterization of adhesive bonded connections in wood structures. Pages 197–207 *in* H. L. M. dos Reis, ed. Nondestructive testing and evaluation for manufacturing and construction. Hemisphere Publishing Co., New York, NY.

———, ———, M. J. CHICA, AND D. W. CASTER. 1990b. Nondestructive evaluation of adhesive bond strength of finger joints in structural lumber using the acousto-ultrasonic approach. J. Acoustic Emission 9(3):196–202.

VARY, A. 1989. The acousto-ultrasonic approach. Pages 1–21 *in* J. C. Duke, Jr., ed. Acousto-ultrasonics: Theory and applications. Plenum Press, New York, NY.

VARY, A., AND R. F. LARK. 1979. Correlation of fiber composite tensile strength with the ultrasonic stress wave factor. J. Testing Eval. 7(4):85–191.