ACOUSTO-ULTRASONIC ASSESSMENT OF INTERNAL DECAY IN GLULAM BEAMS

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ABSTRACT

An acousto-ultrasonic (AU) through-transmission technique was evaluated for assessing brown-rot decay in Douglas-fir glulam beams that had been removed from service. The effect of decay on different AU signal features was compared to that from normal variations in wood, such as growth ring angle, knots, and moisture gradient. The analysis was based on measurement of velocity, attenuation, shape, and frequency content of the received signals. All of the studied signal features were correlated with the degree of decay; however, they were affected by natural characteristics of wood. Attenuation and signal shape were more affected by the growth ring angle variations and knots than were velocity and frequency features. The effect of knots depended upon size, type, orientation, and distance from the surface. A steep moisture gradient obscured the detection of small degrees of decay, with the greatest effect on signal shape and frequency parameters. This study suggests that multiple signal feature analysis can be used to distinguish decay from certain types of natural wood characteristics such as growth ring angle variations and knots.

Keywords: Acousto-ultrasonics, brown-rot decay, glulam, growth ring angle, moisture gradient, knot, wood

INTRODUCTION

The natural variation of wood-based materials is a major difficulty when using nondestructive methods in decay detection (Szymani and McDonald 1981; Zabel and Morrell 1992). Many wood characteristics, such as grain angle, density, moisture content variations, and presence of defects, such as knots, wane, and resin pockets may mask the presence of decay. There are also many different types of decay fungi that affect wood constituents differently, and therefore their response to detection. The third major difficulty in nondestructive detection of decay in wood products is the effect of environmental conditions, such as temperature of the material.

Many nondestructive methods have been

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studied for internal decay detection of different types of wood products. These techniques include radiation (X-ray, gamma ray), electrical (low frequency and DC conductance, microwave), and acoustic (stress wave, sonic, and ultrasonic, including acoustic emission and acousto-ultrasonics) (Szymani and McDonald 1981; Ross and Pellerin 1991; Beall and Wilcox 1987; Wilcox 1988; Patton-Mallory and DeGroot 1990; Zabel and Morrell 1992; Madsen 1994). The radiation methods are affected primarily by density and moisture content of wood. Electrical methods depend on conductivity and dielectric properties, which are especially affected by moisture content below the fiber saturation point (FSP). Acoustic methods are largely dependent on mechanical properties (modulus of elasticity and modulus of rupture) and density of wood. The differentiation of decay from other defects and natural wood variability affects all of the NDE methods, however; in otherwise defect-free wood, all of the methods are sensitive to the presence of decay. The type of wood product, environmental conditions, and costs are major factors that determine which detection technique is used.

The objective of this study was to examine the feasibility of through-transmission acousto-ultrasonics to detect internal decay in glulam beams. The efficiency of decay detection was determined through feature extraction and analysis of signals measured through glulam beams having different types of wood characteristics and defects, and various amounts of decay. The major wood characteristics studied were moisture gradient, growth ring angle, and knots.

BACKGROUND

It has been shown that acoustic waves propagating in wood are affected by the natural variability of wood and by different types of defects. Through studies made with different frequencies and types of wood products, it has been possible to estimate the effect of the wood characteristics on elastic wave propagation.

Signal processing methods for AU

Acousto-ultrasonics (AU) was developed by combining ultrasonic and acoustic emission techniques. As in conventional through-transmission ultrasonics, a pulse or burst is injected into a material and the response is captured at another point. The received signal is then processed by extracting different types of signal waveform parameters (signal features). The received signal is a result of multiple reflections, wave interactions, and mode changes (Vary 1989). Different characteristics of the signal can be described by parameters that are measures of signal attenuation, velocity, shape, and frequency content. In this study, four different features were selected from a larger set to represent the maximum of information and the minimum of redundancies (Biernacki 1991; Kiernan and Duke 1988).

Root mean square (RMS) voltage was used as a measure of signal energy. The inverse of RMS voltage can be used to approximate signal attenuation. RMS can be calculated from:

$$RMS = \frac{\sqrt{\sum V_i^2}}{n} \tag{1}$$

where n is a number of measured data points from signal and V_i is the voltage at point i. Signal velocity was calculated from transit time (t), the time from the transmitter to the receiver, with the assumption of a direct signal path of distance, d:

$$v = \frac{d}{t} \tag{2}$$

The threshold level for the received signal was placed just above the noise level to detect the first arrival of the signal.

Signals can also be processed by determining moments from the following expression:

$$M_n = \int y(x)x^n \, dx \tag{3}$$

where n is the moment order and x is the particular domain of the signal (for example, time or frequency).

The zeroth moment is the area of the waveform. By dividing the first moment by the zeroth moment, we obtain a centroid. The time centroid (TC) is sometimes referred to as "mean time," when the bulk of the signal energy is received and is therefore related to its shape. When an ultrasonic signal is injected into a flawless medium, most of its energy is typically near the beginning of the waveform. Reflections and mode changes occur from material flaws, causing a skewing of the signal in time domain.

Power spectrum characteristics can also be expressed by the nth moment of the waveform in Eq. (3), where x is represented by frequency. Spectral moments are combined measures of amplitude and frequency; with a larger n, more weight is placed on frequency. Physically, the frequency centroid indicates the center frequency of the signal relative to the amount of energy.

Results from previous studies

The effect of moisture content (MC) on velocity has been studied by a number of researchers, who have shown that the velocity of acoustic waves decreases with moisture content up to the FSP (Gerhards 1982; Sakai et al. 1990; Minimisawa and Ozawa 1994; Mishiro 1996a; Olivito 1996). For moisture contents above FSP, velocity is constant in the longitudinal grain direction (Sakai et al. 1990). Attenuation is constant below 18% moisture content and then increases above this level. Quarles (1990) found similar attenuation effects in the transverse direction. Moisture gradient was found to have a similar effect as average moisture content on ultrasonic velocity in all directions when desorption occurred through the measuring face (Mishiro 1996a). Previously, James (1986) had shown that the transverse moisture gradient had a strong effect on longitudinal velocity during desorption of green wood.

Both growth ring angle (GRA) and grain orientation affect wave propagation. The effect of the growth ring angle in softwoods is nonlinear with the maximum attenuation at 45–60 degrees (Suzuki and Sasaki 1990; Biernacki and Beall 1993; Mishiro 1996b). The effect of GRA on velocity and attenuation is species-dependent, with hardwoods having a more linear relationship than softwoods (Quarles 1990; Mishiro 1996c). Attenuation increases and the wave velocity decreases with increasing grain angle (Lemaster and Dornfield 1987; Biernacki and Beall 1993). Attenuation is more sensitive than velocity to material anisotropy (Bucur and Feeney 1992).

The skewing and focusing effects of acoustic wave propagation are illustrated by studies in which acoustic wave was refracted in the fiber direction (Lord et al. 1988; Green 1991; and Dickens et al. 1996). Gerhards (1982) found that the grain orientation near knots affected velocity measurement, and the wavefront led in the grain direction or through knots. Sandoz (1989) showed that increasing the knot area decreases the acoustic velocity in the longitudinal direction.

The effect of density on the acoustic wave is dependent on species, wood structure, and the measurement direction (Gerhards 1982; Bucur 1983; Mishiro 1996c). However, Mishiro (1996c) found no consistent relationship between density and velocity in the longitudinal or transverse directions.

Ultrasonic wave velocity decreases and attenuation increases with the presence of decay (Gerhards 1982; Wilcox 1988; Pellerin et al. 1985; Patton-Mallory and DeGroot 1990; Bauer et al. 1991; Lemaster and Wilcox 1993; Beall et al. 1994). The velocity change is affected by the type of fungus and the wood species. Also, the ratio of high to low frequency components decreases and the time centroid increases with increasing decay.

MATERIALS AND METHODS

The glulam sections were cut from each of four Douglas-fir beams that had been previ-

TABLE 1. *Properties of the analyzed glulam specimens (* estimated values using regression model).*

Specimen	Average (Std Dev) of MC (%)	Average (Std Dev) of density (kg/m^3)	Decayed area (%)	Dimensions W × H × L (mm)
1A	*15.8 (4.5)	460 (68)	40	128 × 460 × 640
1B	*12.9 (2.6)	460 (68)	40	125 × 460 × 640
1C	10.2 (0.5)	460 (68)	40	123 × 460 × 640
2	9.8 (0.5)	404 (106)	71	174 × 310 × 710
3	9.6 (0.4)	419 (79)	42	173 × 335 × 620
4 (control)	9.1 (0.2)	511 (48)	0	130 × 300 × 320

ously removed from service. Three beams had portions that were decayed by a brown-rot fungus (*Antrodia xantha*), as shown in Table 1. All specimens contained other defects, such as knots and checks or splits. Specimen 1 was exposed to an environment to develop three different desorption moisture gradients over a four-month period (Table 1). The beams contained laminates with growth ring angle (GRA) variations as shown in Fig. 1. Before scanning, the glulams were marked with 50- by 50-mm grids for subsequent sectioning as shown in Fig. 2.

The through-transmission AU system (Fig. 3) consisted of a PC-based signal acquisition system, transducers, amplifiers, a signal source, and a positioning device, which was based on a previously developed system (Biernacki and Beall 1993). Two piezoelectric transducers were used, a resonant 175 kHz (AET AC175L) transmitter and a wideband (Dunegan SE1025-H) receiver. The transducers were mounted in a probe assembly, which transmitted the coupling force without applying excessive force to the transducers. A plastic waveguide coupled the transducer and a 25-mm-diameter silicone rubber disc, which was used as a dry couplant between the probe and the wood. The coupling pressure (0.3 MPa) was applied from the transducer holder through a thick (15-mm) soft-rubber spring, which self-aligned the coupling surface to the material. The clamping system consisted of manually controlled air cylinders, and used a milling machine table as a stable attachment and positioning base for the clamping system, AU probes, and specimen.

The specimens were scanned in steps of 10 mm transversely and 12.8 mm longitudinally. Signal averaging of 256 waveforms at each step was used to increase the signal to noise ratio. After the AU measurements, the specimens were cut into 50- × 50-mm sections on the surface and with a length equal to the glulam width for analysis of moisture, density, decay, and other defects. Table 2 shows the numbers of grid elements scanned and examined for decay and moisture content. Defects were determined visually, and decay was confirmed both visually and microscopically. The volumetric portions ("volumetric loss") of each glulam specimen were estimated by vi-

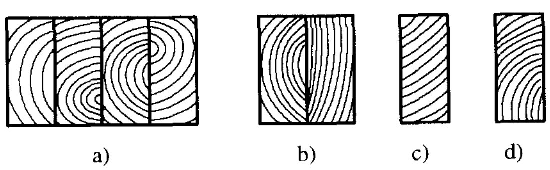

FIG. 1. Examples of growth ring angle (GRA) variations included in cross sections: a) specimen 1A–C, b) specimen 3, c) specimen 4, and d) specimen 2.

TABLE 2. *Number of specimens AU-scanned and removed for decay and moisture content analysis. The locations of specimens in each category are shown in Fig. 2.*

Glulam	AU-scanned (whole specimens)	AU-scanned (whole + partial specimens)	Examined for decay	Examined for decay and MC
1	60	80	96	96
2	36	60	65	48
3	30	50	60	48
4 (control)	16	24	36	36

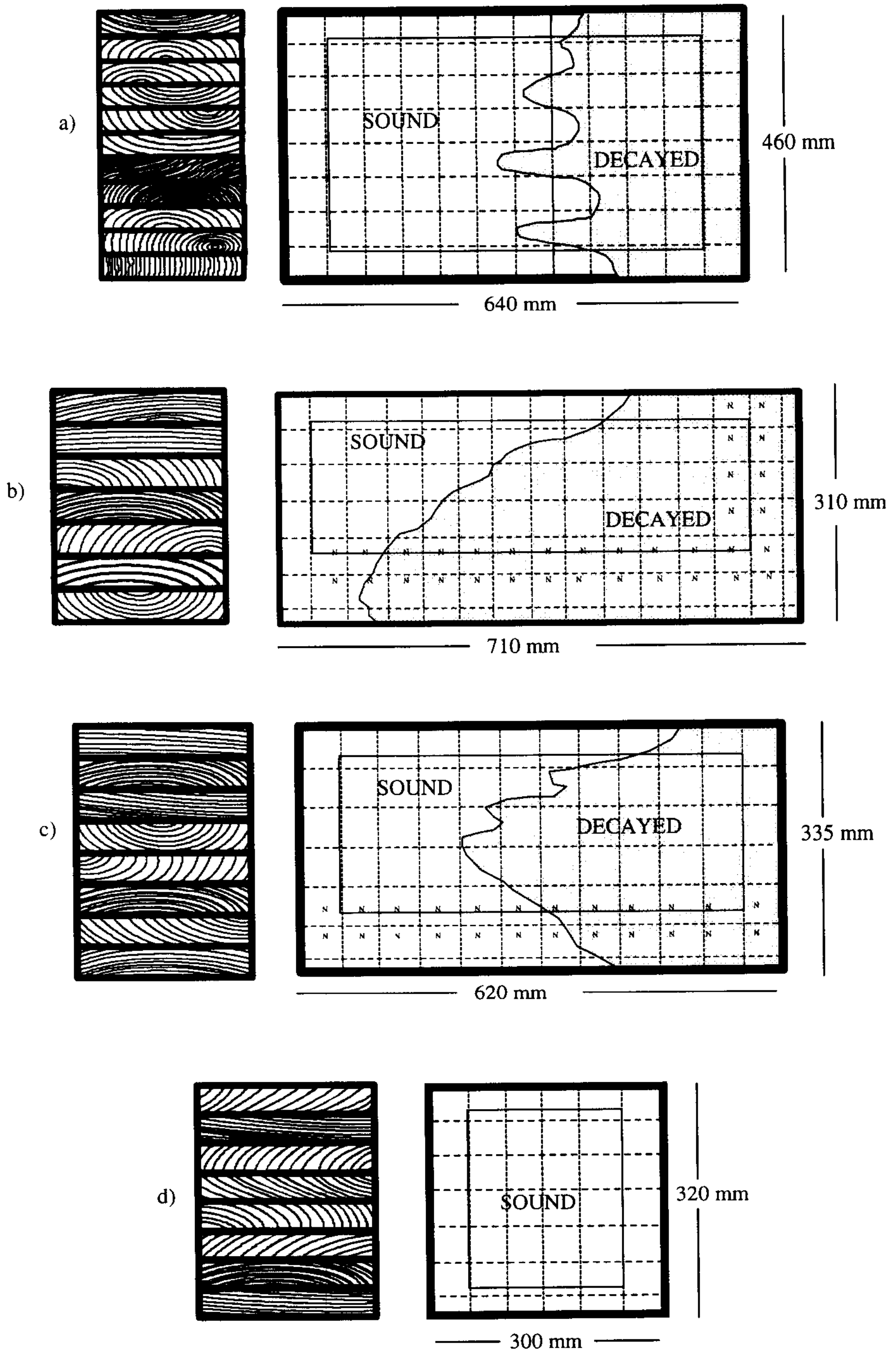

FIG. 2. Elements of glulams marked for subsequent 50-by-50-mm specimen removal. The AU-scanned area is within the solid rectangle and includes whole as well as portions of laminates. Those elements marked with "n" were not measured for moisture content.

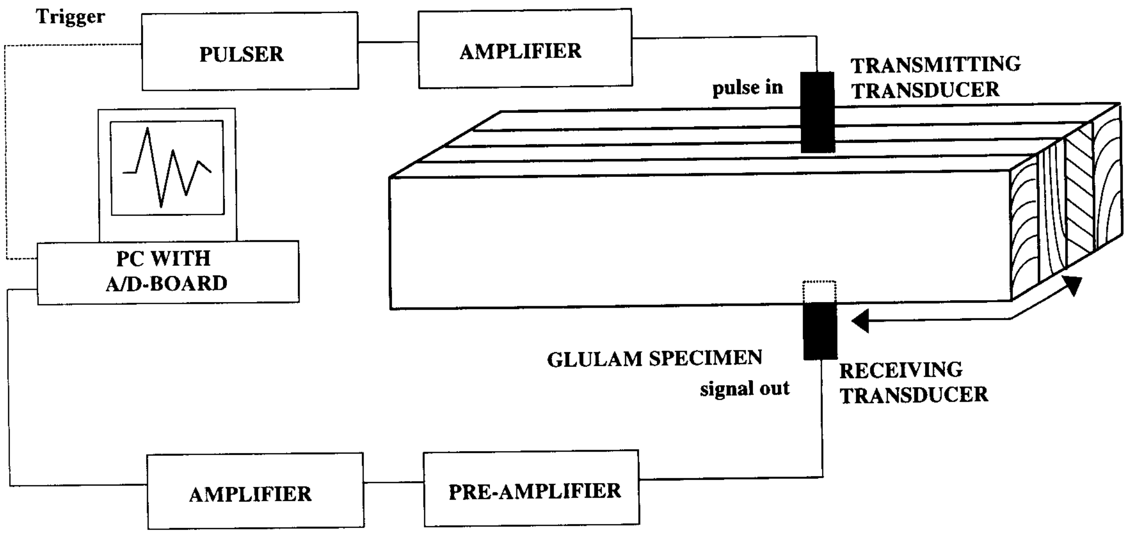

FIG. 3. A schematic diagram of the AU-measurement system.

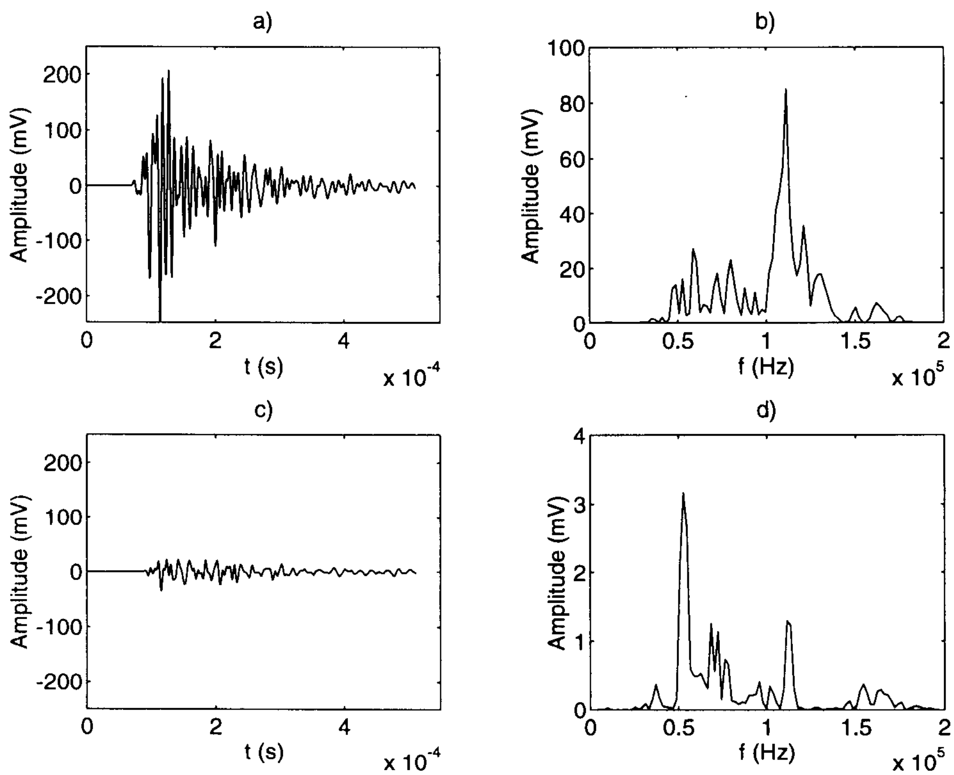

FIG. 4. Responses of received AU signals for specimen 1C. Sound region: time domain (a) and frequency domain (b). Decayed region (30% of the cross section decayed): time domain (c) and frequency domain (d).

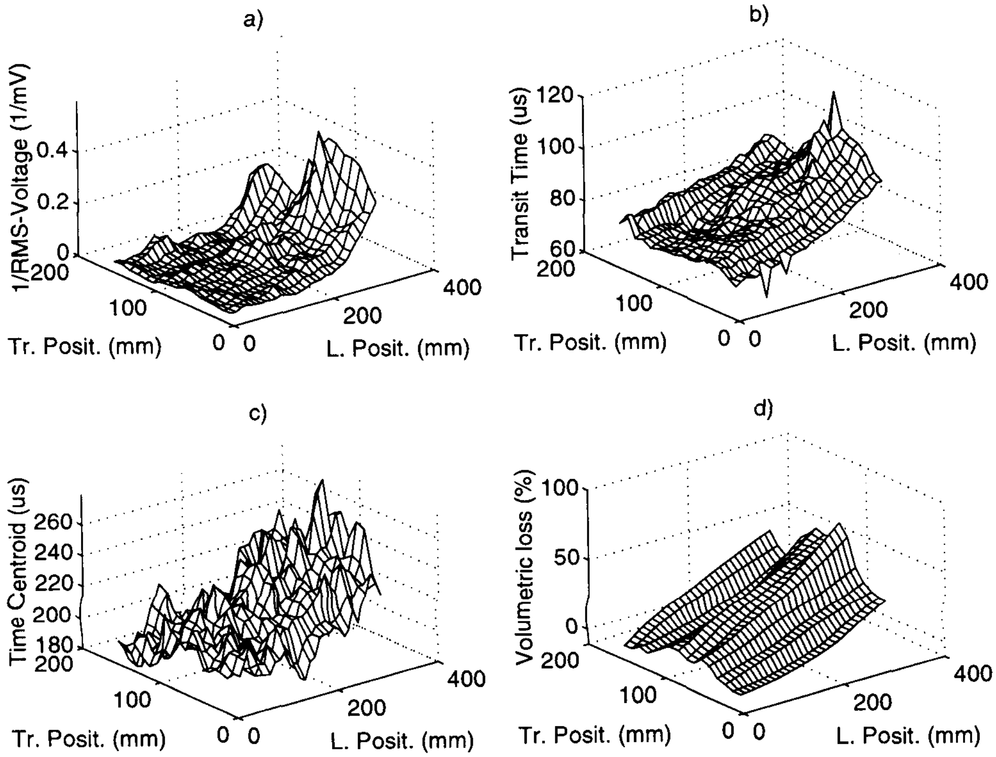

FIG. 5. Plots of AU parameters and volumetric (visually determined) fraction of decay in the same region of specimen 1A. GRA of this plot is shown in Fig. 1a (0 mm in Tr. position represents right edge; 160 mm is the left edge). a) inverse RMS (attenuation), b) transit time, c) time centroid, d) average volumetric decay loss.

sual analysis of the sections, where the presence of any level of decay was considered part of the loss (Table 1, Fig. 2). This visual method was found to be particularly effective in determining the decay boundaries in Douglas-fir in a previous study (Wilcox 1988). The mass loss caused by decay was estimated as the ratio of average mass of material in longitudinally separated sound and decayed regions along each laminate or laminates. Since there was little variation in density along the grain direction, the sound wood density was assumed to be representative of the original density of the decayed material. Moisture content was determined using standard gravimetric methods, and moisture gradients were measured using a conductance moisture meter at three depths (10, 20, and 30 mm) on both sides at the center and near both ends of the beam after the AU measurements. The moisture gradient was estimated with a parabolic model using six moisture content readings near the surface and the average moisture content.

RESULTS AND DISCUSSION

The effects of decay, growth ring angle, moisture gradient, and knots were analyzed for their effects on AU signals and the interference of the wood variables on detection of decay.

Decay

Figure 4 shows the effect of decay on the time and frequency domain of received signals for Specimen 1C, having 30% decay. Typically, decay causes a substantial decrease in the time-domain signal—in this case, approximately two orders of magnitude. In the frequency domain, the high frequency content of

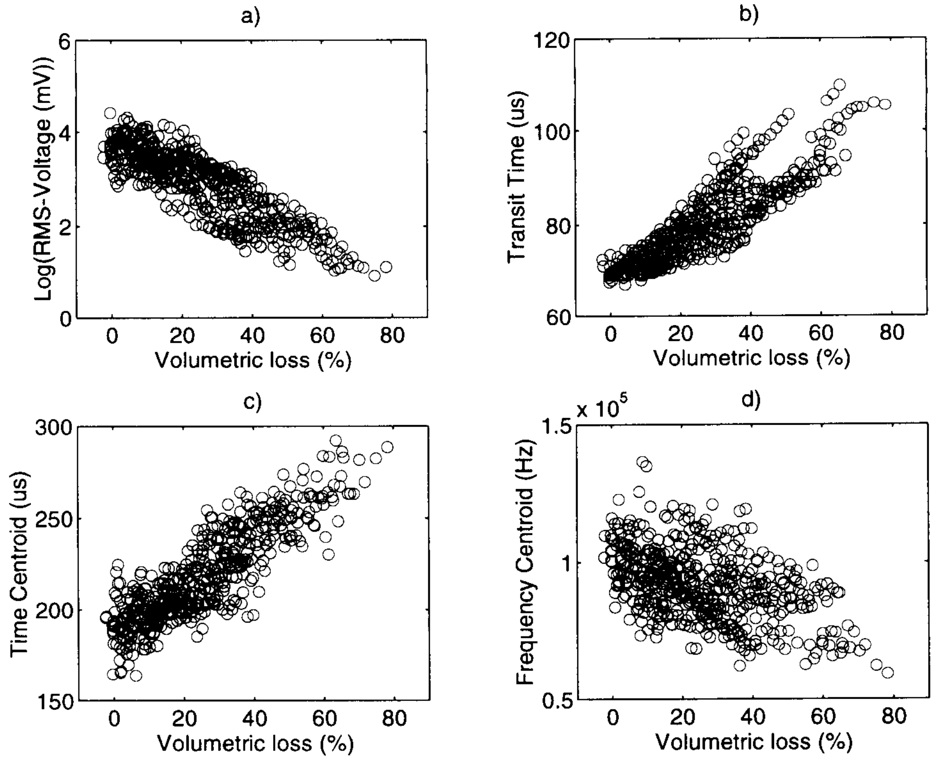

FIG. 6. Relationships of AU parameters and to the volumetric fraction (visually determined) of decay in the direct signal path for single AU measurements in specimen 1B: a) logarithmic RMS-voltage, b) transit time, c) time centroid, d) frequency centroid.

the signal is virtually absent and the amplitude of the peak frequencies is also substantially reduced. Figure 5 shows typical reconstructed profiles of the relationship of AU parameters to the degree of decay (averaged through the cross section) in the central portion of specimen 1A. Both RMS and transit time have profiles similar to that of decay; time centroid appears to have a high degree of variability superposed on the profile. The measured regions included variables such as moisture gradients, knots, and growth ring angles.

Figure 6 gives the relationship of single AU measurements to the volumetric (visual) decay loss estimated from a particular 50- by 50-mm element. The correlation coefficients were −0.85, 0.88, 0.86, and −0.47 for RMS, transit time, time centroid, and frequency centroid, respectively. Clearly, only frequency centroid had a poor correlation; all others were very similar in their relationships.

The relationship between AU features and small amounts of decay is shown in Fig. 7 for clear wood and constant GRA (one laminate scanned in the longitudinal direction in three different transverse points). The correlation coefficients were −0.86, 0.97, 0.87, and −0.75 for RMS, transit time, time centroid, and frequency centroid, respectively. In linear regression with low levels of decay, transit time is superior to other parameters. Although the correlation coefficient for RMS was lower than transit time, this was caused by the nonlinear relationship with degree of decay; the change of RMS from 0 to 5% decay was substantially greater than that of other AU parameters.

Correlations of AU parameter values and decay were determined for glulams 1–3 (Table

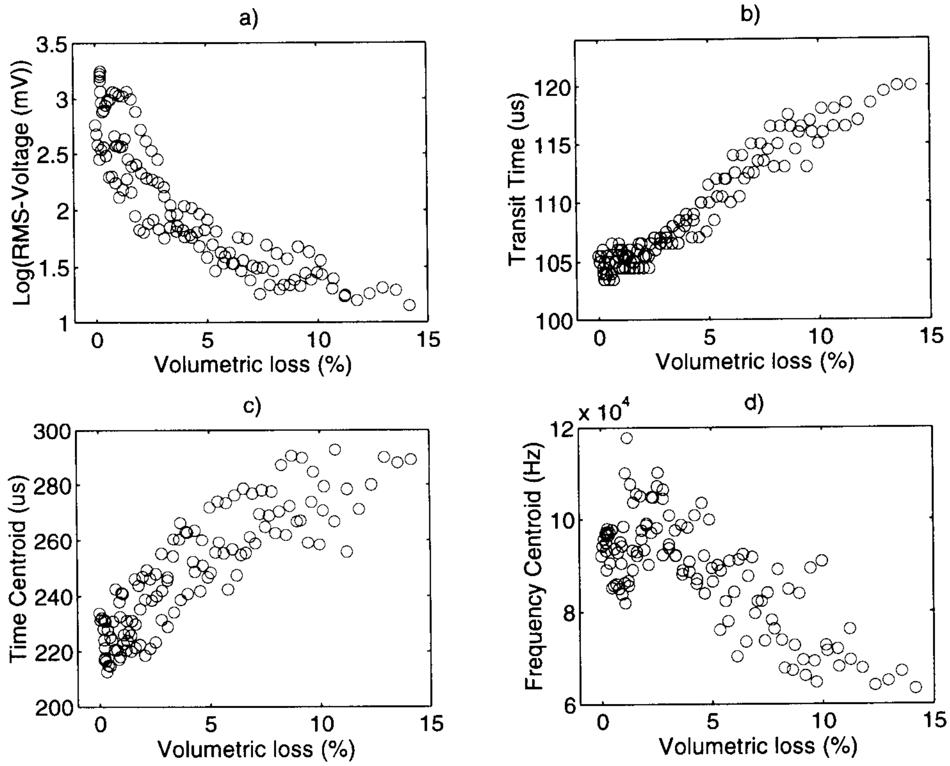

FIG. 7. Relationships between AU features and small degrees of the volumetric fraction (visually determined) of decay in the signal path for specimen 2 with constant GRA (Fig. 2d): a) logarithm of RMS voltage, b) transit time, c) time centroid, d) frequency centroid.

3). The effect of averaging the data for each 50- by 50-mm specimen is significant for all AU parameters. All three time-domain parameters had similar correlation coefficients; that for the frequency centroid was relatively low. The correlation coefficient between visually and gravimetrically analyzed decay was 0.89, which shows consistency between two methods that involve secondary determinations of the degree of decay.

TABLE 3. *Correlation coefficients between AU signal features and visually determined decay.* r_{single} *is the coefficient for individual (point) AU parameter measurements for the three decayed glulams (1 to 3).* $r_{average}$ is the coefficient for average values obtained over the 50- by 50-mm faces of the specimens, also for the three glulams.

AU-signal feature	r_{single}	$r_{average}$
RMS-Voltage	−0.85	−0.96
Transit Time	0.88	0.98
Time Centroid	0.86	0.97
Frequency Centroid	−0.50	−0.83

Growth ring angle

The effect of growth ring angle (GRA) on AU measurements was determined by analyzing AU data from areas of 20 laminates with different GRA, but no other interfering characteristics. The laminates included those with relatively constant GRA as well as those that were highly variable. Because of the different patterns of GRA, variation analysis of AU values was used to assess differences between longitudinal and transverse readings on the glulam. Since the GRA is nearly constant longitudinally (within a particular laminate or laminates), a difference in variation means that the AU parameter is affected by the GRA (Ta-

TABLE 4. *Average coefficients of variation (Stand. Dev./Mean) of AU features in longitudinal (CV_l) and transverse directions (CV_t) and their relative differences for sound regions of glulams with varying GRA.*

AU-Signal Feature	CV_l	CV_t	$(CV_t - CV_l)/CV_t$
RMS-Voltage	0.23	0.44	0.47
Transit Time	0.04	0.05	0.21
Time Centroid	0.05	0.37	0.86
Frequency Centroid	0.10	0.15	0.29

ble 4). Signal shape (as represented by time centroid) was the AU feature most affected by the GRA as seen in the transverse variation, but signal energy (as approximated by RMS) had the overall highest variation longitudinally. Transit time was least affected by GRA and frequency centroid was affected only slightly more. Based on these results, RMS has an unacceptable variation from GRA when used as the lone parameter. Time centroid is also unacceptable because of the large variation in the transverse variations.

The effect of GRA can also be illustrated by comparing Figs. 6 and 7, showing that it is possible to detect even very small amounts of decay in clear wood that has no variation in GRA. The effect of a changing GRA is shown in Fig. 8 for changes in AU signal features when scanning from a region of a nearly purely tangential GRA into one with a variable GRA (Fig. 2b). Under this changing GRA, attenuation and time centroid decreased, and transit time increased, but there was no obvious change in frequency content.

Moisture gradient

The purpose of generating different moisture gradients in the same specimen was to

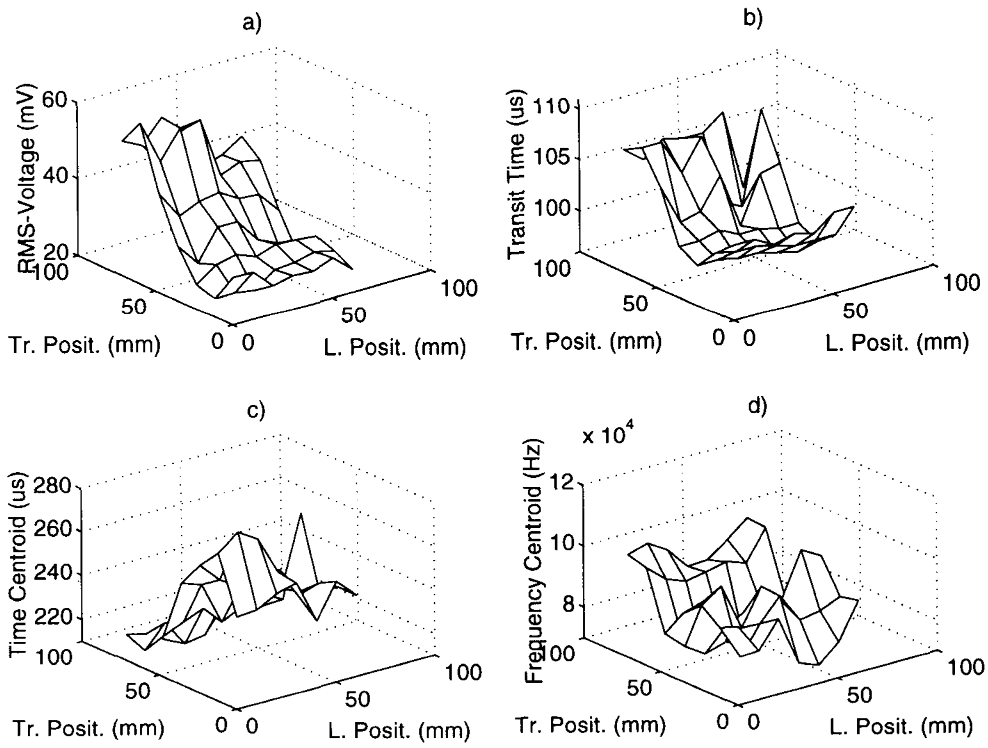

FIG. 8. Effect of GRA on signal features for a sound region of specimen 3 having two different GRA arrangements (0 mm in Tr. position is right edge of Fig. 1b; 90 mm is left edge): a) RMS voltage, b) transit time, c) time centroid, d) frequency centroid.

TABLE 5. *Effect of moisture gradient on averaged AU signal feature values between sound (SF_s) and decayed (SF_d) regions. 100% × (SF_d − SF_s)/SF_s.*

	10% decayed			20% decayed			30% decayed		
Moisture Gradient	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small
RMS-voltage	−31	−42	−42	−64	−65	−70	−85	−84	−87
Transit time	7	8	5	15	17	19	28	31	33
Time centroid	0	5	8	8	13	18	14	24	24
Frequency centroid	−2	−5	−5	−5	−11	−23	−15	−22	−21

determine the independent effect of moisture content on detection of decay. For all tests, the highest moisture content was at the center (1A: 27%; 1B: 19%; 1C: 12%; also referred to as Large, Medium, and Small, respectively). An area of 160 × 250 mm was scanned longitudinally, with a total of 16 scans. In each measurement, the surface had an air-dried moisture content (about 10%) and was free from decay. Differences in signal features between sound portions and three decay levels with three different moisture gradients are shown in Table 5. Each AU signal feature value was obtained for each moisture content gradient by averaging the measurements in sound and decayed regions in the same center portion of the specimens. At a specific level of decay, RMS and transit time had minor variations caused by the moisture gradients and were clearly sensitive to the level of decay. How-

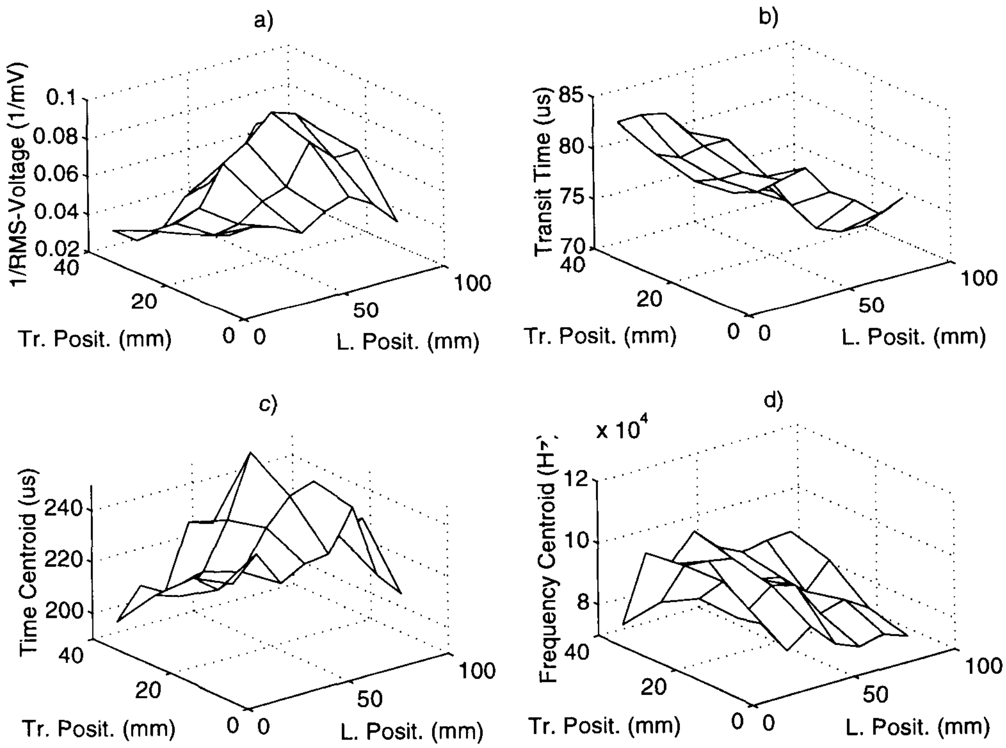

FIG. 9. Signal features for a 30-mm-diameter sound internal knot oriented 45° to the signal path in specimen 4: a) inverse RMS-voltage (attenuation), b) transit time, c) time centroid, d) frequency centroid. The center of the knot is located in the middle of the plots; GRA is shown in Fig. 1c.

ever, both frequency centroid and time centroid were affected by moisture, such that the data overlapped between adjacent decay levels (10 and 20%, and 20 and 30%), and were highly variable with the moisture gradient at each decay level.

Knots

Figure 9 shows typical AU signal feature values for a 30-mm-dia internal sound knot located about 12 mm from the transmitter in a scan over a 40- by 100-mm area in Specimen 4 (control). The knot is in the center of the plots; its effect is readily discernible from the large change in RMS shown in Fig. 9a. Comparison of AU measurements at the knot location with those of clear wood shows that attenuation and shape parameters (Fig. 9a, c) were affected more than those for apparent velocity (from transit time) and frequency (Fig. 9b, d), although velocity was the least affected parameter. The major factor that affects signal attenuation and transit time is believed to be the grain interfaces at knot boundaries. Also, the three-dimensional patterns for a knot are quite different from decay. While knots are confined to single laminates, decay typically changes along the grain and often extends into adjacent laminates (see Figs. 2, 5c, d); therefore, pattern recognition could be used to separate the presence of decay from that of a knot.

In Table 6, it can be seen that, of the four signal features, only transit time could be used to separate the effects of knots from small amounts of decay (10% of the section). The knot was located in a laminate having a 45° GRA; therefore, the axis (the longitudinal grain direction of the knot) was also at 45° to the signal path. The decrease in transit time is caused by the added longitudinal grain component, which would produce a substantially greater velocity. Therefore, transit time could be used to distinguish the presence of a knot, since all other defects would increase the transit time. If a knot were more aligned with the signal path, it would cause lower attenuation, lower time centroid, and higher frequency centroid, all of which are opposite to the effect of decay. Because knots affect attenuation and shape parameters similarly to the effect of small decay pockets, it is not possible to distinguish these defects by using only one signal feature.

CONCLUSIONS

In agreement with previous studies, all four of the AU signal features were affected by decay: attenuation and time centroid increased, and apparent velocity and frequency centroid decreased. In the case of high levels of decay, when the signal attenuation was high, the time centroid decreased because of the substantial reduction in signal duration. This was particularly evident when the decay occupied more than 60% of the particular signal path. Averaging increased the correlations and the detection accuracy but reduced the spatial resolution for all four AU parameters. Local wood defects reduced the correlation, especially when no signal averaging was used.

It was found that the signal attenuation (1/RMS) parameter was the most sensitive feature for decay detection. Unfortunately, the natural wood variability and other defects caused similar effects on the signals. Time centroid and attenuation had similar responses to knots and GRA. The effect of decay on time centroid and transit time was also similar under conditions of low moisture content, constant GRA, and the absence of other defects. The signal velocity parameter was not as sen-

TABLE 6. *Comparative effect of the presence of a knot (specimen 4) with a small amount of decay (10% of the section) for the averaged signal features of specimen 1C. Relative AU values were based on 100%* $\times$ $(SF_i - SF_s)/SF_s$, *where* SF_i *= signal feature value with a knot or decay and* SF_s = value in sound region.

AU-signal feature	Decay	Sound knot
RMS-voltage	−42	−49
Transit time	5	−9
Time centroid	8	9
Frequency centroid	−5	−3

sitive to other wood variables making it the most reliable parameter if only one signal feature is used for decay detection. The frequency centroid parameter was the most useful in detecting small levels of decay. In an automated analysis, a frequency parameter would be very useful since the effect of specimen thickness on the frequency content was clearly less than for other AU parameters. In detection of small amounts of decay, a high internal moisture content gradient reduced the response of the signal features, with time centroid and frequency the parameters most affected.

The results suggest that it is not possible to detect decay with any degree of precision by using only individual parameter analysis because of the effect of natural variability and defects in the wood. The study also shows that multiple parameter analysis can be used for differentiating decay from some natural wood characteristics, such as certain types of knots and growth ring angle variations, which is not possible by using single parameters.

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