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ULTRASONIC NONDESTRUCTIVE EVALUATION OF WOOD AND WOOD PRODUCTS - PAST, PRESENT AND FUTURE

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Abstract:
Three generations of ultrasonic evaluation techniques for wood and wood products are presented, first (past), second (present), and third (projected future). The first generation involved a simple interpretation of a signal passing through the material of interest. The transition from first to second generation was largely from the advent of digital techniques and the ability to analyze specific and/or multiple features of received signals of different characteristics. For the third generation, a guided wave approach, nonlinear ultrasonic methods, and advanced on-line transducer assemblies are discussed, with emphasis on air-coupling techniques.

Key words: *ultrasound; guided waves; non-linear methods; air-coupling.*

INTRODUCTION

Nondestructive evaluation techniques are somewhat limited for wood and wood products. The application of ultrasonic technologies to these materials has been substantially aided by developments in assessing the integrity of fiber-reinforced plastics (FRP), which have many characteristics similar to those of wood, both of which require special techniques to detect internal flaws. One of the key ultrasonic technologies used for wood-based materials is acousto-ultrasonics (AU), which has a reasonable history of use in laboratory research and progress toward industrial use in the past several decades. The past and current uses of AU have been largely in laboratory assessment of properties of wood-based materials, with a few industrial trials (Beall 1987). The future needs of AU lies in the application for monitoring or controlling industrial processes primarily for newly developing structural wood materials.

In North America, there has been a substantial trend from solid wood to engineered wood as structural material for residential and non-residential structures. Fig. 1 provides an overview of the development of engineered wood products.

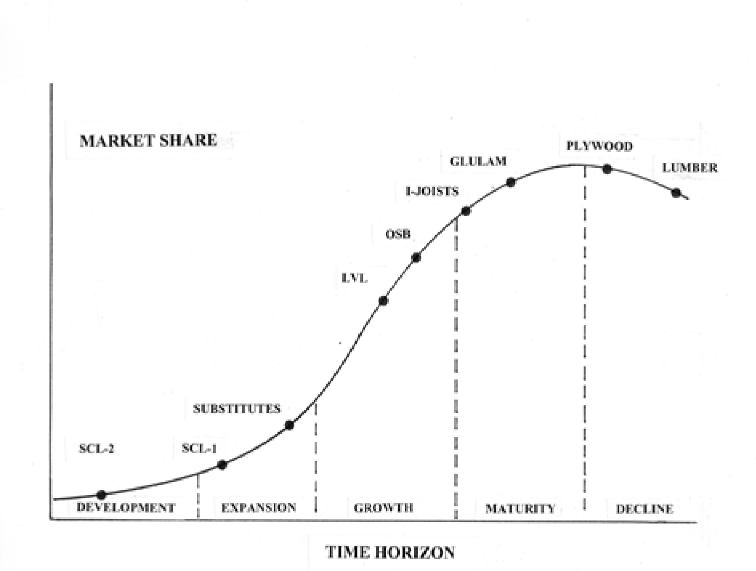

Fig. 1.
Engineering wood products life cycles. LVL is laminated veneer lumber; SCL is structural composite lumber (first and second generation).

For example, in 1980, North American oriented strandboard (OSB) panel production was 0.7 Mm^3. By 1990, it was 7.0 Mm^3 and by 2005, had grown to 22.1 Mm^3 (TECO 2011). Twenty-five years ago, engineered wood (mostly glulam, I-joists, and LVL) was less than 1% of the combined total of structural lumber and engineered wood. By 1990, engineered wood had grown to over 1.6 Mm^3, representing 1.7% of structural wood products. In 2005, engineered wood was estimated to be nearly 6%, over 7 Mm^3. It has been projected that by 2100, solid wood will be virtually absent from structural wood materials.

The transition to structural engineered composites poses a challenge for quality assessment and for determining mechanical properties. As an example of this challenge, the typical current quality control procedure for OSB is to sample two panels in a 12-h shift, which is about 0.03% of the total number of boards produced. Because many of these materials will be made in continuous processes, the critical need is consistency of material properties using nondestructive evaluation techniques that can identify critical defects (e.g., voids, non-uniform distributions of adhesive etc.) and monitor consistency of material properties such as density. Because of the severe environments where large volumes of these materials are manufactured, there are currently no reliable nondestructive testing systems capable of providing on-line sensing for quality assurance.

One of the key challenges of ultrasonic nondestructive evaluation of the developing composite structural wood materials is the need to cope with the inherent gradients of density and elastic properties, and to interrogate using non-contacting techniques. The major objective of the chapter is to provide an overview of past developments and a review of more advanced ultrasonic techniques that can be applied to newer structural wood products.

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Acousto-ultrasonics

In acousto-ultrasonics (AU), 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 can be processed by extracting different types of signal waveform parameters. The received signal is a result of multiple reflections, wave interactions, and mode changes (Vary and Bowles 1989). By stimulating the transmitter, very consistent stress waves can be injected into the material. AU also has the capability of controlling the input frequency. There are a number of options in AU for transmitter/receiver combinations/configurations that depend on attenuation, dispersion, frequency sensitivities, and waveform processing needs. For example, the simplest arrangement could be a pair of transducers at the same resonant frequency, with spike pulsing of the transmitter. At the other extreme, a spike pulse could be used to energize a wideband transmitter, with a wideband receiver to capture the signal to obtain the broadest frequency interrogation and greatest opportunity for waveform processing. Intermediate is the use of tone-burst to inject a much greater amount of energy at a particular frequency.

First Generation Signal Generation and Processing

An arbitrary means of separating the first from subsequent generations of AU was the predominate use of analog circuitry. In the original AU method, a stress wave factor (SWF) was determined in which the number of threshold crossings were counted:

$$SWF = trn \tag{1}$$

Where t is the time interval; r is the rate of pulsing; and n is the number of oscillations crossing a threshold. For example in the waveform below, the number of crossings of the first gridline, if that were the threshold, would be 18:

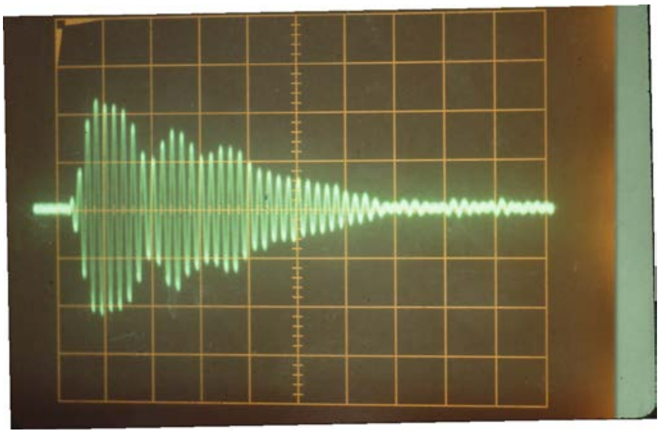

Fig. 2.
Output waveform modified by transmission through a material from the input of a pulsed resonant transducer.

Also, analog root mean square (RMS) values could also be routinely obtained as a measure of signal energy. The inverse of RMS voltage can be used to approximate signal attenuation. RMS can be calculated from:

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

where *V* is the voltage value at point *i*. Signal velocity is calculated from transit time (*t*), the time from the transmitter to the receiver, based on the assumption of a direct signal path of distance, *d*:

$$v = \frac{d}{t} \tag{3}$$

In order to detect the first arrival, the threshold level for the received signal must be placed just above the noise level. In highly attenuating and dispersive materials, such as wood, the leading edge of the waveform may be difficult to detect, decreasing the apparent velocity. It should also be obvious that the assumption of the direct signal path underestimates the actual velocity in perhaps every case.

Second Generation Signal Generation and Processing

With the advent of digital techniques to capture and analyze signals, it became possible to calculate values of specific or multiple parameters.

Moment Analysis

The most widely used method to obtain many features of signals is through moment analysis:

$$M_n = \int y(x)x^n dx \tag{4}$$

Where n is the moment order and x is the particular domain of the signal (for example, time or frequency). The zeroth moment is simply the area of the waveform. By dividing the first moment by the zeroth moment, we obtain a centroid. The time centroid is sometimes referred to as the mean time, 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 boundaries and 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, 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 received energy.

Modified Impact-Echo Decay Rate Analysis

A typical impact-echo test system is composed of three components: impact source; receiving transducer; and waveform analyzer to capture the transient output of the transducer, store the digitized waveforms, and perform signal analysis. The use of impact-echo testing methods has been traditionally limited to the detection of parallel interfaces located at a finite depth, which are sufficiently reflective and have a significant acoustic impedance mismatch (>24%). Some of these limitations can be overcome by proper attenuation measurements and analysis of the output decaying signal for a longer period of time. The attenuation measurements alleviate the dependence on source repeatability issues and overcome many of the geometric limitations imposed by the test object (Egle 1981). With a broadband receiving transducer, the frequency of the peaks in the amplitude spectrum can be readily analyzed to determine the depth of the reflecting interfaces. This approach is less dependent on the location, duration, and wavelength energy content of the source and can be used over an extended spectral range including higher frequencies.

A time domain signal collected from an impact, partitioned (windowed), and processed by an FFT algorithm. For each frequency, a spectral feature is calculated, such as amplitude, area under the power spectral density curve for a frequency band, and energy. This process is performed as many times as the number of window increments, until the last window contains the final point in the total time domain signal. The spectral feature values at frequencies of interest, are plotted against time for the duration of the signal. An exponentially decaying function with respect to time can then then fitted to these data:

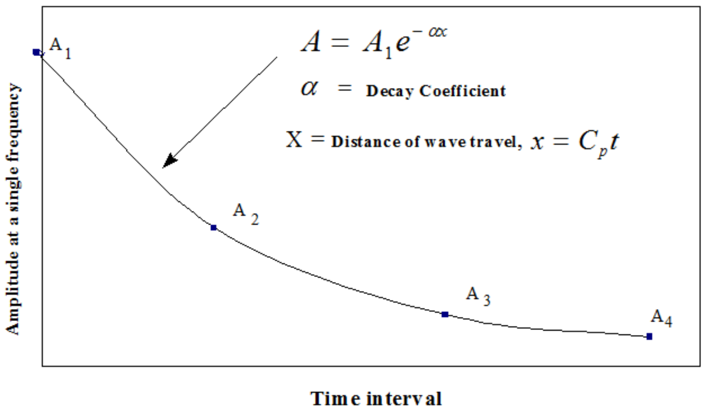

Fig. 3.
Development of a characteristic curve for a desired feature (A) from windowed frequency analysis.

The coefficient α of each plot represents the decay (attenuation) at that location, and the initial amplitude, A_1, represents the initial window value of the selected feature for that frequency. This technique has recently been used in the detection and assessment of wood decay in glulam beams (Senalik *et al.* 2010).

Third Generation Signal Generation and Processing

In this section some emerging nondestructive evaluation/characterization methods with potential application to current and future engineered wood products are discussed. These include the use of a guided wave approach, nonlinear ultrasonic methods, and advanced on-line transducer assemblies (Beall and Reis 2013).

Guided Waves

In an infinite isotropic solid medium only two types of independent wave propagation exist, dilatational and shear waves, both of which are non-dispersive and have constant velocities. When the dimensions are close to the wavelength, the wave becomes dispersive and is called a guided wave. Guided waves have benefits such as: (1) inspection over long distances, (2) ability to allow mode and frequency tuning to optimize defect detection, and (3) inspection of structures that are multi-layered. Traditionally, the guided wave approach in plate-like structures assumes that the material properties remain constant throughout the thickness (Rose 1999). This assumption is not valid in engineered wood because most of the products have a gradation of material properties through their thickness, caused largely by the higher material density caused by the pressing process:

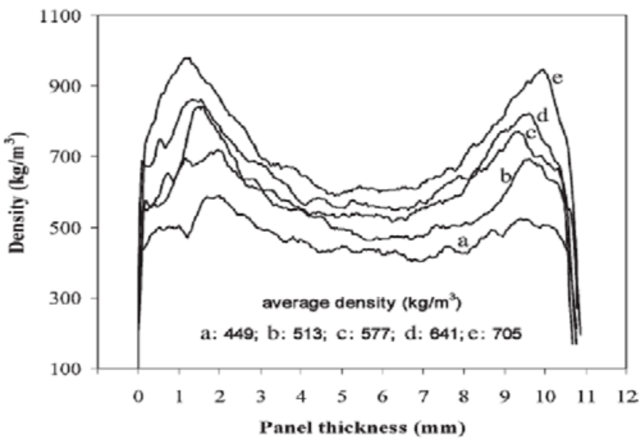

Fig. 4.
Density gradient of a typical wood-based composite reflecting the compression that occurs in pressing.

Elastodynamic wave propagation in graded materials (where acoustic impedance is broadened spatially) is a rarely treated problem. For example, at the boundary of two media an incident pulse normal to the interface is split in two parts: the first continues propagating in the material and the second is reflected. The amplitude ratio of the reflected and transmitted parts is governed only by the normalized difference in the acoustic impedance of the two media, provided that the impedance change is a pure step function in space. However, in the graded materials, the ratio of the transmitted and reflected parts is frequency dependent. In the case of engineered wood materials, the thickness of the plate-like structure is graded, and by definition of guided waves, the wavelength is of the same order of magnitude as the plate thickness.

Nonlinear Ultrasonics

Homogeneous materials are assumed to have linear elasticity, where the presence of defects leads to phase or amplitude variation of the ultrasonic wave, but with the frequency of the received signals the same as that transmitted. A major difficulty in ultrasonic evaluation of wood-based materials is that they are non-homogeneous and frequently vary in elastic properties with depth, and the frequency of the received signal differs from that of the transmitter. This is consistent with nonlinear ultrasonics, which implies a nonlinear transformation of the ultrasonic wave energy. Nonlinear elasticity introduces three independent elastic constants, referred to as *third-order elastic constants* (TOECs) that describe the nonlinear stress-strain response of an isotropic material (Murnaghan 1937). Different sets of independent TOECs have been proposed by several authors including A, B, and C, used by Landau and Lifshitz (1959), which are a linear combination of the l, m, and n Murnaghan constants (1937).

Various ultrasonic methods to measure material nonlinearities have been developed. The first makes use of the acousto-elastic effect, where the material nonlinear response results from variations in ultrasonic propagation velocity with applied strain (Bernstein and Toupin 1961). By applying different wave types and measuring velocity in unstrained and strained states all three TOECs can be measured. The problems are the need to strain the test specimen and the difficulty of measuring small changes in propagation time and distance to determine velocity. The second and most widely used method for nonlinearity is the harmonic generation (Buck *et al.* 1978). When ultrasonic energy is injected, harmonics of the input are generated from material nonlinearities during propagation, typically appearing as integer multiples above the input signal. The normalized harmonic amplitude has been found to correlate with the amount of fatigue damage (Kim *et al.* 2006) or plastic deformation (Pruell and Kim 2007). A third technique, non-collinear mixing, proposed by Jones and Kobett (1963), is based on material nonlinearities causing interactions between two intercepting waves, leading to the generation of a third wave with a frequency and wave-vector equal to the sum of the incident wave frequencies and wave-vectors. This technique has several advantages: (1) it is much less sensitive to instrumentation nonlinearities from spacial selectivity; (2) it has modal, frequency, and directional selectivity, and (3) the level of underlying system nonlinearity can be measured directly by summing the responses of the incident waves excited separately. There is a potential fourth method, vibro-acoustic spectroscopy, that takes advantage of the modulation of the wave generated by the sending transducer by either a stress field induced by external loads or by low-frequency forced vibration (Korotkov *et al.* 1994).

Advanced On-line Transducer Assemblies

The development of on-line ultrasonic systems for wood products has been impeded by the lack of commercial grade air-coupled transducer systems. This is particularly important because these products do not lend themselves to immersion and the use of liquid coupling. Most air-coupled ultrasonic methods use conventional piezoelectric elements with careful impedance matching or capacitance transducers, but several orders of magnitude of acoustic impedance mismatch exists. Furthermore, the attenuation of sound traveling through air increases rapidly for frequencies above ~1 MHz. Several solutions have been attempted including multilayered silicon rubbers as a half-wavelength matching layer on a piezoelectric transducer (Kelly *et al.* 2001), SiO_2-aerogel as an impedance matching layer (Kraub *et al.* 1994), and using piezocomposite active elements of different piezoceramic fractions, shapes and distributions (Reily and Hayward 1991). Typically, these work for narrow bandwidths and require much tuning effort.

Capacitive transducers have received increased interest because of their higher sensitivity and wide bandwidth. Capacitive ultrasonic transducers consist of a thin polymer membrane (metalized) and a conducting patterned backplate. The very small mechanical impedance of the thin membrane greatly reduces the impedance mismatch. The metalized polymer membrane is attached to the patterned backplate for both the sending and the receiving transducer. Applying a transient voltage induces vibrations in the membrane, which generates ultrasound in air. Similarly, receiving the vibrating sound signals is achieved using the same transducer as a reciprocal device. Figure 5 shows the use of five air-coupled ultrasonic transducers configurations to interrogate engineered wood panels using guided waves. Figures 5a, b, and d represent through-transmission arrangements to interrogate differing amounts of a moving panel-type system, any of which could include single or multiple transmitting frequencies. Figures 5c and e are different methods to interrogate gradients within the material.

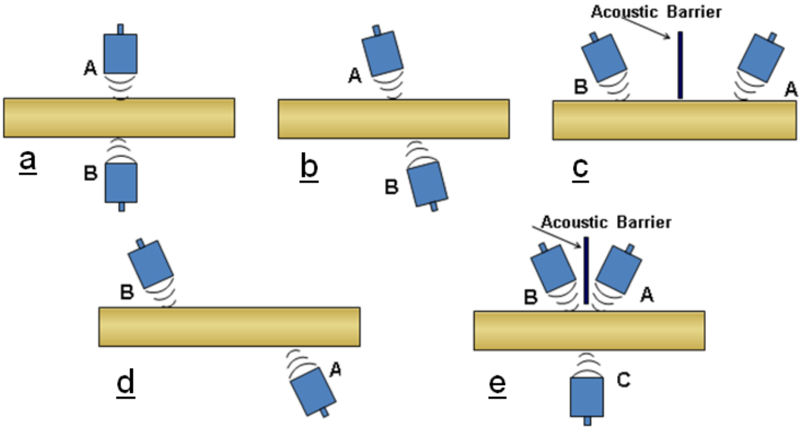

Fig. 5.
Different configurations of air-coupled transducer systems to interrogate average or gradient values for moving continuous or panel-type materials.

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