Noncontact ultrasound detection of exotic insects in wood packing materials

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Abstract

Nondestructive methods for detection of wood-boring insects such as the Asian longhorned beetle (ALB), *Anoplophora glabripennis* (Coleoptera: Cerambycidae) inside solid wood packing materials is a valuable tool in the fight to exclude exotic insects from attacking a nation's timber resources. Nondestructive, non-contact, ultrasound was investigated as a potential method for detection of cerambycid larvae in solid wood packing materials. If successful, this technology could be used by port inspectors attempting to detect and eliminate the unintentional importation of exotic pests in commercial trade shipping materials. One-inch-thick samples of aspen (*Populus* spp.) and red pine (*Pinus resinosa*) wood with and without cerambycid larvae in holes were scanned with 200-kHz ultrasound waves above wood fiber saturation and at low moisture conditions. A pair of noncontact transducers acting as the emitter and the receiver was placed on either side of the wood sample. The resulting transmission data were used to produce ultrasonic images with a state-of-the-art, signal analyzer system for nondestructive sensing applications. We successfully generated detailed c-scan images for all wood samples, regardless of species and wood moisture condition. Artificially drilled holes in the wood samples could also be clearly identified in the c-scans. Although both the larva and its movement could be detected in the images when placed on top of the wood, neither was detectable when placed inside the sample. We concluded that with the current technology, 200-kHz ultrasound imaging is not a feasible method for detecting insects in wood packing material. Future research focusing on other forest product or entomology applications such as density measurements of plywood, grading of lumber, and measurement of larval feeding rates derived from changes in tunnel characteristics should be undertaken as these applications may prove feasible with the current state of this technology.

Solid wood packing materials such as pallets and crates are used to transport products around the world. Destructive wood-boring pests such as the Asian longhorned beetle (ALB), *Anoplophora glabripennis* (Coleoptera: Cerambycidae) are arriving undetected inside the wood used to make these shipping materials. Arrival of exotic insects at distant ports is becoming an increasing threat to global timber resources (Nowak et al. 2001). One example is the accidental introduction of ALB from China into both North America (USDA 1996) and Europe (Krehan 2002) during the early to mid-1990s. Efforts are still underway to eradicate this destructive pest from hardwood trees on both continents (Krehan 2002, Markham 2002,). New technologies to efficiently detect and intercept exotic pests at port cities where large volumes of imported goods arrive could be very useful tools (Mastro 1999).

Nondestructive, noncontact ultrasound was proposed as a method to detect the

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*Forest Products Society Member.

Forest Prod. J. 55(6):33-37

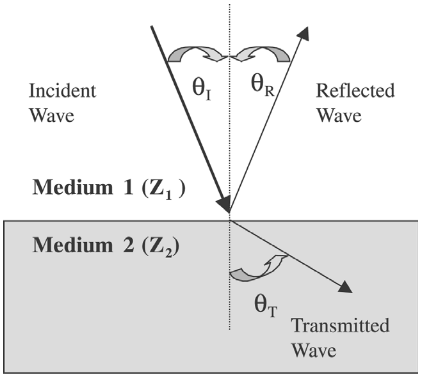

Figure 1. — Schematic of material/wave interaction at a boundary between two mediums.

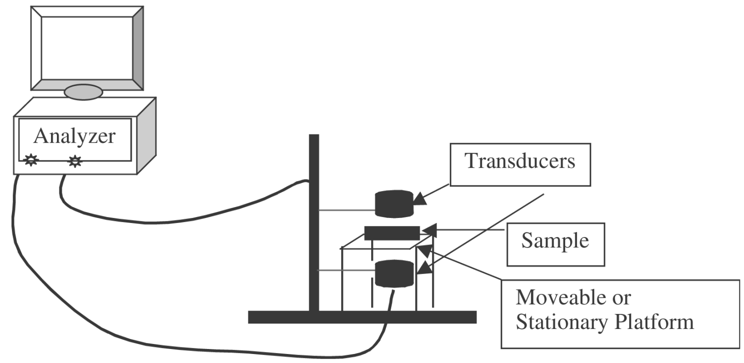

Figure 2. — NCA 1000 analyzer and non-contact transducer set-up.

presence of cerambycids hitchhiking in solid wood packing materials. In the wood-processing industry, research on the application of ultrasound in the pulp and paper industry has been conducted (Brodeur and Gerhardstein 1998). In addition, Wu et al. (2000) investigated the use of noncontact ultrasound to evaluate oriented strandboard. East Alabama Lumber (Wood Technology 2000) has used ultrasound technology in its milling process to optimize the cutting of cants up to 12 inches thick. However, no literature is available on the use of noncontact ultrasound technology for the detection of wood-boring insects in wood.

The use of noncontact ultrasound testing is generally limited because of inherent problems with the air-material interface. As with all acoustic waves, ultrasound transmission is attenuated to some degree by the bulk material (liquid, solid, or gas) it travels through, as well as the interfaces between media it encounters. Through bulk materials (Ensminger 1988), wave intensity (I) at a specific distance, x, from its origin can be mathematically described as:

$$I = I_o e^{-2\alpha x} \quad [\mathbf{1}]$$

where I_o is the initial intensity of the wave, and α is the attenuation coefficient for the medium in which the wave is traveling (Eq. [**1**]). The attenuation coefficient is proportionally dependent on frequency. At the interfaces, a portion of the ultrasonic energy is transmitted, while the remainder is reflected (**Fig. 1**). The intensity (I) (Eq. [**2**]) (Bhardwaj 1986) of the transmitted portion of the wave is directly proportional to the transmission coefficient T (Eq. [**3**]), which in turn is dependent upon the acoustic impedance (Z_1 and Z_2) of the two mediums. The acoustic impedance of a material is dependent upon density (ρ) and velocity (c) (Eq. [**4**]):

$$I = I_0 T \quad [\mathbf{2}]$$

$$T = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \quad [\mathbf{3}]$$

$$Z = \rho c \quad [\mathbf{4}]$$

The acoustic impedance (Bhardwaj 2002) of air (415 Rayl) is significantly smaller than of solid media such as wood ($1.57{\times}10^6$ Rayl). Consequently, the portion of the energy transmitted through these interfaces is very small. For example, for one air/wood interface, 0.1 percent of the initial energy is transmitted through the interface. Over the years, many different techniques have been employed to overcome the challenges of impedance mismatch. In the last few years, Second Wave Systems (Boalsburg, PA) developed highly efficient transducers capable of producing high acoustic pressures in gases combined with a signal processing system that overcame many of these obstacles. Noncontact (air-coupled) transducers in combination with a complex signal processing system has made nondestructive testing of free-standing samples in air possible in many cases (Bhardwaj 2002).

We investigated the use of noncontact ultrasound over an area of wood to capture ultrasonic images indicative of beetle activity, such as larval galleries and pupal chambers. In addition, we attempted to image additional details, such as the presence of larvae within the wood to determine whether they were alive or dead. If successful, this technology would be useful for port inspectors screening solid wood packing material for unintentional importation of exotic insects.

Materials and methods

Ultrasonic equipment

A state-of-the-art ultrasound system (Model NCA 1000, Second Wave Systems, Boalsburg, PA) with a computer processor, a sample platform (movable or stationary), transducer stands, and cables were used for all experiments (**Fig. 2**). Two noncontact transducers were set 150 mm apart. One focused transducer (NCT102-FL150 Ultran Laboratories, Inc., Boalsburg, PA) emitted the 200-kHz signal, which traveled through an air layer, the sample, and another air layer, before being captured by a second transducer of the same type. The integrated response (IR_m) was then calculated from the transmission readings by the NCA 1000 analyzer (as described below) and a c-scan image was generated from these computed IR_m values. The NCA 1000 system settings were adjusted within the following instrumentation ranges: 188 to 225 kHz frequency, 73 to 112 bandwidth, 300 to 650 µs duration, 10 to 25 µs alternate duration, 50 to 75 amplitude, 45 percent chirp A, 45 percent chirp B, and step index of 0.5 mm.

The integrated response (Wu et al. 2000, Bhardwaj 2002) for noncontact transducer experiments was calculated in the following manner. Integration of the area under the first peak is the power corresponding to the transmitted energy. Both the power corresponding to the transmitted energy in the air column alone (IR_a) and the power corresponding to the transmitted energy through the sample (IR_c) placed between the transducers must be calculated. The net power (IR_m) reported is then as follows (Eq. [**5**]):

$$IR_m = IR_c - IR_a \quad [\mathbf{5}]$$

IR_m is thus a measure of the energy attenuated by the material. All integrated

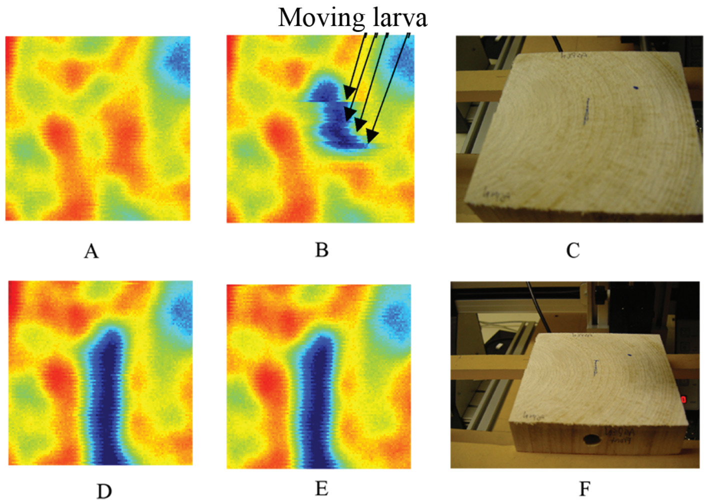

Figure 3. — Transmission-mode 200-kHz c-scan of a 1-inch-thick green aspen sample with MC of 43.7 percent under the following conditions: A) sample alone; B) moving larva on top of the sample; C) photograph of the sample; D) sample with an empty 13/32-inch-diameter hole (~2-1/2-in. deep); E) sample with a larva (1.5 g in weight, 1-1/4-in. long) in the hole; and F) photograph of wood sample with hole.

response data (IR_m, IR_c, and IR_a) are reported in decibels. Decibels (dB) are logarithmic units that describe a ratio. In this case, the ratio compares a reference pressure set by the equipment manufacturer (p_1) to the transmitted ultrasound pressure measured by the receiving transducer (p_2) (Eq. [**6**])

$$20 \log\left(\frac{p_2}{p_1}\right) = IR \qquad [6]$$

For these wood experiments, IR_m is a negative number; the more negative IR_m is the lesser the transmission and the greater the attenuation. Transmission patterns with the computer-generated c-scans ranged in color from red (the higher the transmitted or reflected signal received) to blue (the lower the signal received). Both the IR_m range (dB) and the image itself are reported.

Sample preparation

The wood samples, red pine (*Pinus resinosa*) and aspen (*Populus* spp.), were obtained from harvested trees, processed, and frozen as described in Fleming et al. (2002). Specimen samples of the wood were uniformly cut to 4- by 4- by 1-inch dimensions (+/- 1/16 in. tolerance), since slats used in the manufacture of commercial pallets are often 4 by 1 inches. Moisture content (MC) and specific gravity of the original wood material were determined according to ASTM D 2395 procedures outlined in Method A: Volume by Measurement (ASTM 1996).

To attain the low-MC samples, processed specimens were placed in a forced-air oven maintained at 80°C until reaching a constant ovendry weight basis. Wood samples selected for experimental use were mostly clear of major defects except for an occasional small knot.

Insects

A native species, the cottonwood borer (CWB), *Plectrodera scalator* (Coleoptera: Cerambycidae), was used as a surrogate cerambycid species for our studies because ALB is under quarantine in the United States. The cottonwood borer (CWB) is closely related to ALB and similar in size. The CWB larvae were reared in the laboratory on a meridic insect diet modified from Payne et al. (1975). Our modifications for a 1-liter batch of diet included the addition of 950 mL of water instead of 750 mL, 9.85 g of Wesson's salt without iron phosphate, and 0.15 g of iron phosphate. Larvae were reared individually in plastic or glass jars at 24°C in dark incubators and transferred to fresh jars of diet every 3 to 4 weeks for a minimum of 90 days. After shipment to Penn State University, CWB larvae were maintained for 2 to 3 months at room temperature until needed for the study trials. One pre-diapause larva weighing 1.5 g and reaching 1.25 inches long was used for all experiments in this study.

Ultrasonic trials

The goal of these trials was to produce c-scan images from green or dry wood with or without holes or artificially inserted larvae. In addition, the detection of larval motion was also investigated. Transmission of 200-kHz ultrasound waves was captured through 1-inch-thick green, cross-grain, aspen and red pine (both with and without holes, n = 5), 1-inch-thick dry, cross-grain aspen and red pine (with holes, n = 5), a cerambycid larva (cottonwood borer) on the surface of the wood sample (n = 2), and a larva inside the drilled hole (each wood sample, n = 20). All ultrasonic scans corresponded to 50 mm by 50 mm regions of the wood samples.

Results and discussion

Transmission c-scans were successfully captured through solid 1-inch-thick, 43.7 percent MC green aspen with a beetle larva placed on top of the aspen sample (**Fig. 3B**; IR_m range of -3 to +9 dB). Then, an empty hole of dimensions 13/32 inch in diameter and 2-1/2 inches deep was drilled into the sample and transmission images were captured both with and without a larva in the hole (**Figs. 3D** and **3E**; IR_m range of -3 to +9 dB). For reference, digital photos of the samples are also presented (**Figs. 3C** and **3F**). The lack of homogeneity of the wood itself is quite evident by the mottled image. The larva on top of the wood could be identified by the reduction in ultrasound transmission due to the addition of interfaces (transducer/air, air/larva, larva/air, air/wood, wood/air, air/transducer). Movement of the larva during the scan can also be identified by the discontinuity of the image. The hole is distinguishable because the transmission of the ultrasound through the air pocket was much less than through the relatively solid wood sample. As can be noted in **Figure 3D**, the scan does not show the hole with sharp boundaries. Instead, the hole is shown with wavy boundaries. Upon visual inspection, the inner surface of the hole was ridged and had small splinters of wood sticking into the hole. This is probably due to the drill bit; all of the samples exhibited this phenomenon. By filling the hole with a larva, we were hoping to enhance the ultrasound transmission. However, this did not occur in any of the trials, regardless of wood type or MC. Most likely there was a thin air layer surrounding the larva, creating two wood/air/larva interfaces.

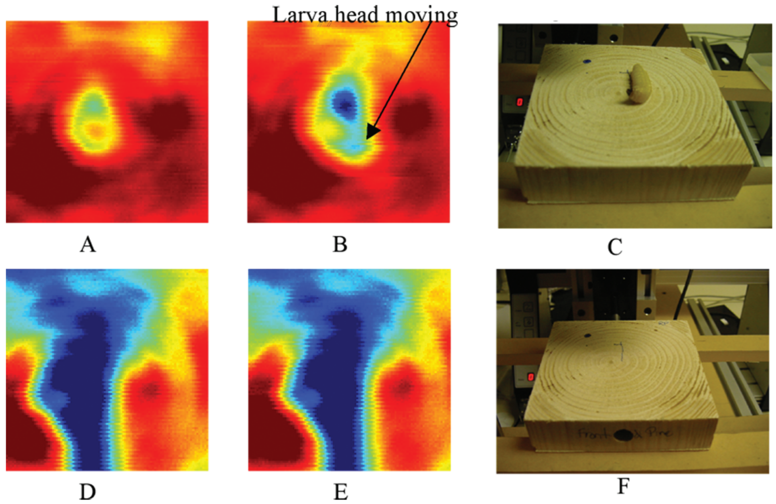

Figure 4. — Transmission-mode 200-kHz c-scan of a 1-inch-thick green red-pine sample with MC of 25.3 percent under the following conditions: A) sample alone; B) larva (only head moving) on top of the sample; C) photograph of the sample; D) sample with an empty 13/32-inch-diameter hole (~2-1/2-in. deep); E) sample with a larva (1.5 g in weight, 1-1/4-in. long) in the hole; and F) photograph of wood sample with hole.

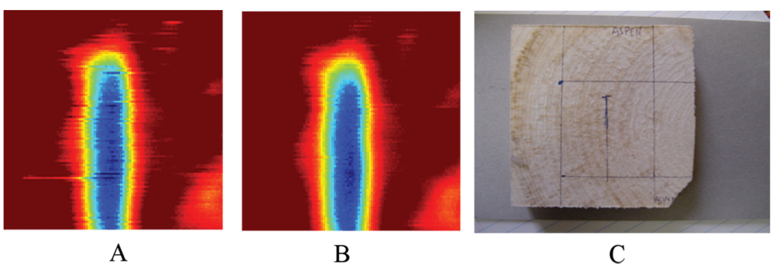

Figure 5. — Transmission-mode 200-kHz c-scan of a 1-inch-thick ovendry aspen sample (MC = 0%) under the following conditions: A) sample with an empty 13/32-inch-diameter hole (~2-1/2-in deep); B) sample with a larva (1.5 g in weight, 1-1/4-in. long) in the hole; and C) photograph of wood sample with hole.

These interfaces presented barriers to ultrasound transmission sufficient to prevent the transducer receiver from detecting a significant difference between the hole alone and the larva-filled hole.

In the same manner, transmission c-scans were captured through 1-inch-thick, 25.3 percent MC, red pine (**Figs. 4A to 4F**), under the following conditions: solid sample alone (-4 to +16 dB range), larva on top of solid sample (-4 to +16 dB range), an empty hole of dimensions 13/32 inch in diameter and 2-1/2 inches deep drilled into the sample (+7 to +16 dB range), and a larva placed in the hole (+7 to +16 dB range). There was a knot in the center of this wood sample, which corresponds to the yellow/light green region in **Figure 4A**. The larva placed on top of this knot was distinguishable from the surrounding wood because it appeared as a larger blue area (**Fig. 4B**). Like the aspen experiments just discussed, the movement of the larva's head was also identifiable by the discontinuity in the scan. Compared to the solid aspen sample, the red pine sample had higher transmission (note the larger area colored red in **Fig. 4A** vs. **Fig. 3A**). This could be due to lower MC in the red pine sample (25.3% vs. 43.7%).

The results of the experiments using ovendried wood support our findings that the transmission of 200-kHz ultrasound is dependent upon MC of the wood. The 1-inch-thick dry aspen sample c-scans show images of the hole alone (**Fig. 5A**; -6 to +9 dB) and a larva in the hole (**Fig. 5B**; -6 to +9dB). Compared to the green aspen, transmission through the wood increased, appearing as a red-der scan. Dry red pine also transmitted a higher signal than with green moisture samples. In the drying process, the pine sample cracked and this crack was evident on the scans. As with the green moisture samples, both the dry pine and the dry aspen sample c-scans did not distinguish between the hole alone and the larva in the hole.

Conclusions

From these ultrasound experiments, several conclusions can be drawn. Noncontact, 200-kHz, ultrasound energy is capable of transmitting a discernable signal through 1-inch-thick red pine wood samples of less than 23 percent MC and 1-inch-thick aspen samples of less than 45 percent MC. Detailed c-scan images can be generated at this frequency for both wood species. Artificially drilled holes in the wood samples could be identified in the c-scans. Both the larva itself and its movement could also be recognized when the larva was placed on top of the wood. However, neither the larva nor its movement could be identified with noncontact ultrasound transmission when the larva was inside an artificially drilled tunnel. This is probably due to the energy loss at the wood/air and air/larva interfaces inside the holes. Therefore, the final conclusion reached is that noncontact, 200-kHz ultrasonic energy is not a feasible alternative for detecting live beetle larvae in lumber at the current state of the technology.

Since noncontact ultrasound imaging might prove to be useful for other forest product or entomology applications, such as density measurements for plywood, grading of lumber, or measurement of larval feeding rates derived from changes in tunnel characteristics, future research focusing on these applications is suggested by the authors. In addition, systematic empirical studies that focus on the frequency-dependence of noncontact ultrasonic attenuation by wood features such as natural cell geometry, cracks, knots, as well as environmental effects are recommended in order to facilitate potential wood-processing applications.

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