Effects of Thickness and Grain on the Amplitude of Airborne Ultrasonics

by

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Abstract

Currently, hides and leather are visually inspected and graded for quality, usable area, and sale price. However, visual inspection is not reliable for detecting defects that are hidden inside the material. Development of a non-contact nondestructive method to accurately evaluate the quality of hides and leather is urgently needed. We previously reported the research results for airborne ultrasonic (AU) testing using non-contact transducers to evaluate the quality of hides and leather. The ability of AU testing was demonstrated for revealing defects in hides and leather that were difficult to be found during visual inspection. We also reported results on AU inspection using a statistical data/cluster analysis technique, in which leather and hide defects were depicted as color-coded amplitude maps, or "C-scans." Recently new research was carried out to study the effects of transducer frequency, thickness of leather, and AU gain on the resultant AU amplitude received, which was shown in a C-scan imagine. Observation showed that a lower frequency of 100 KHz yielded better transmission of AU waves through samples and the AU gain should be less than -5dB. In addition, the amplitude of the C-scan decreased with the thickness of the samples. This study has provided a significant guidance for successful AU testing.

Introduction

An objective and nondestructive method is needed to accurately evaluate the quality of hides and leather.[1] Airborne Ultrasonic (AU) methods have been used extensively in the inspection of lumber and composites.[2, 3] AU testing involves pulsing ultrasonic waves and measuring the amplitude of those waves transmitted through the material. We believe by using the through transmission mode, more useful information can be extracted from the AU scan, particularly for hides, which are covered by hair. When performing AU testing, it is important to understand how effectively ultrasonic waves pass from one medium to another. AU waves must travel from air, which is a medium with low acoustic impedance, to a medium such as hides and leather with considerably higher acoustic impedance. Therefore the selections of the proper AU transducers and frequency are critical to achieve enough penetration of ultrasonic waves in order to extract important information related to the structure and properties of leather, such as the amount of defects, morphology, strength and softness.[4]

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When an ultrasonic wave is passed from one medium to another, generally most of the energy is reflected and the remaining energy is transmitted. Some of the transmitted energy through the medium is attenuated by the medium itself. However, the amount of energy absorbed in attenuation is insignificant compared to the amount of energy reflected at the boundary layers of the medium or mediums and therefore attenuation is not of intrinsic value to this study. The physical quantity that governs the reflected and transmitted relationship is referred to as acoustic impedance (Z).

$$Z = \rho V \qquad (1)$$

where

ρ = density of medium

V = velocity of sound through medium

The velocity of the sound through a medium (v) is proportional to $(E/\rho)^{0.5}$, where (E) is the elastic constant and (E) is the density of medium.[5] Because of this relationship, Equation (1) can be reformulated as follows:

$$Z = (\rho E)^{1/2} \qquad (2)$$

This square-root relationship indicates the acoustic impedance of a material and is governed by its density and elasticity. Ultrasonic waves are reflected at boundaries where there is a difference in the acoustic impedance (Z) of the materials on each side of the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with Equation 3. The value produced is known as the acoustic reflection coefficient (R).

$$R = (Z_1-Z_2)^2 / (Z_1+Z_2)^2 \qquad (3)$$

Where:

Z_1 = acoustic impedance of medium 1

Z_2 = acoustic impedance of medium 2

Multiplying R by 100 yields the amount of energy reflected as a percentage of the original energy (R%). On the other hand, the transmission coefficient is calculated by subtracting the reflection coefficient from one because the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy. The higher the R value, the greater the percentage of energy will be reflected at the interface or boundary between one medium and another. For example, air (0.0004×10^6 Kg m^{-2} s^{-1}) has a very low acoustical impedance, water (1.52×10^6 Kg m^{-2} s^{-1}) has a higher impedance than air, and steel (45.8×10^6 Kg m^{-2} s^{-1}) has an even higher impedance than water.[6] When ultrasonic waves are passed from water to steel, R% is approximately 87.8%; whereas, when ultrasonic waves are passed from air to steel, R% is approximately 99.9% indicating that almost all of the ultrasonic energy is reflected when passing ultrasonic waves from air to a solid such as steel, making air a very poor ultrasonic couplant. Therefore, it is predictable that the mismatch of acoustic impedance weakens the sound wave transmission. Defects such as voids, insect damage, and brands will increase R% and therefore decrease the amplitude of the wave transmitted through the material, which will show up in AU images such as C-scans.

Our previous studies indicated that AU testing could reveal the presence of defects in the leather or any other physical discontinuity that could affect the leather quality.[4, 8] The variations in the AU quantities, such as amplitude (AMP) or time of flight (TOF) were colored coded into C-scan images to reveal the location and shape of the defects or some other physical discontinuity that could affect the hides or leather quality. For example, this AU imaging technique revealed the presence of defects in the hides created by healed wounds and other physical discontinuities that could affect the leather quality. We also used software to translate the C-scan of a hide into numeric values that reflect the extent of defects and integrity of hides, which could then be used as a more objective grading system. Results showed that although there were many graphic presentations that could be used in the testing, among them, it appeared that time of flight (TOF) provided some interesting images that revealed more information about defects such as vertical fibers.[8] To perfect AU methods for hides and leather inspections, new research was recently carried out to study the effects of transducer frequency, thickness of leather, and AU gain on the resultant AU amplitude received, which was color coded into a C-scan image.

EXPERIMENTAL

The AU test system consisted of two ultrasonic transducers approximately 3 cm apart, a transmitter (model: NCG200-D50 or NCG100-D38, the Ultran Group, State College, PA) with a diameter of 50 mm or 38 mm pulsed with a tone burst through a power amplifier, and a receiver (model: NCG200-D25 or NCG100-D25) with a diameter of 25 mm connected to a preamplifier were mounted on a computer-controlled X-Y scanner using the software UTWIN version E1.81 (NDT Automation, Princeton Jct., NJ) that allowed the transducer/receiver array to be moved over the entire surface of the hide. The samples were clamped tautly across a frame with two parallel bars in order to minimize any slack in the sample.

The samples used for showing the effects of AU frequency on C-scan imagines were shoe upper crust from shaved, 1.8-2.0 mm, wet blue. A leather crust sample (retanned, colored and fatliquored from shaved, 1.8-2.0 mm, wet blue) with a brand and an air dried vegetable tanned split from a commercial vegetable tannery were used as well.

Converting the C-scan images into numeric data is the key step to enable one to quantitatively represent the defective regions in hides or leather. Clusters with similar amplitudes were analyzed to identify regions of interest and quantitatively assess the C-scan data. Two amplitude threshold regions of interest selected were 20 to 50% and 80 to 100%. It was demonstrated previously that the 20 to 50% amplitude range correlated with Nissan Shirley stiffness values, but not any of the other mechanical property values.[4] The minimum cluster size was set at 0.5 mm^2 or 2 pixels in which groups of pixels 0.5 mm^2 or 2 pixels or bigger is considered a cluster. The cluster neighborhood was set to 2.5 mm or 5 pixels, which indicates the minimum distance between the closest edge points in a cluster or group of pixels. If two clusters are closer than the set distance of 5 pixels, (set cluster neighborhood value) they are considered to be one cluster. The total area of all the clusters in the set amplitude threshold is calculated and represented as the percent area within the defined amplitude threshold. All samples were tested in a conditioned room set at 23 ± 2°C and 50 ± 5% RH.

RESULTS AND DISCUSSION

For one AU scanning result, there are various AU quantities that can be displayed as a function of time or sample position. The velocity, amplitude, and duration of ultrasonic waves measured by the receiver changed with the material properties of test samples. The C-scan is very commonly used in AU testing, in which the transmitted AU pulses were captured and the amplitudes of the transmitted pulses were mapped using pseudo color from the maximum amplitude in gate 1 or gate 2 set on the A-scan.[8] The A-scan presents the waveform of the received signal and gate 1 is set to the first wave and gate 2 is set to the second wave. The C-scan images in Figure 1 were based on gate 1, because the gate 1 signals come directly from the transmitted waves without reflections. The C-scan image shown in Figure 1a is proportional to the amplitude of the signal with dark brown being the highest amplitude and deep blue being the lowest. This method is commonly applied to airborne ultrasonics. As shown in Figure 1, C-scans for a Shoe Upper Weight Crust, the 100 KHz pulsing frequency yields a lot more transmitted signals (Figure 1a) than those from the 200 KHz pulsing frequency (Figure 1b). A pulsing frequency of 100 KHz was chosen hereafter, because it was low enough so ultrasonic attenuation (scatter and absorption) is greatly reduced to levels which permit ultrasound to readily propagate through both air and the samples of hides and leather targeted for inspection, yet high enough so satisfactorily small-diameter, well-collimated ultrasonic beams can be generated by acceptably small-sized transducers.

Figure 2 shows a C-scan image (Figure 2b) of crust leather with defects (Figure 2a). The defects such as part of the scar and bending marks are clearly shown in the C-scan image. Previously using higher frequencies than 100 KHz, the C-scan image failed to show these defects.

To better handle the AU test, a study was performed to understand the effects of thickness and gain on the received amplitudes. It was noted that through many tests that the thickness of samples and gain of the AU instrument have a significant effect on the test results of the C-scan images. Therefore a systematic experiment was set up to evaluate the effects. The thickness of leather, a natural material, varies as shown in Figure 3.

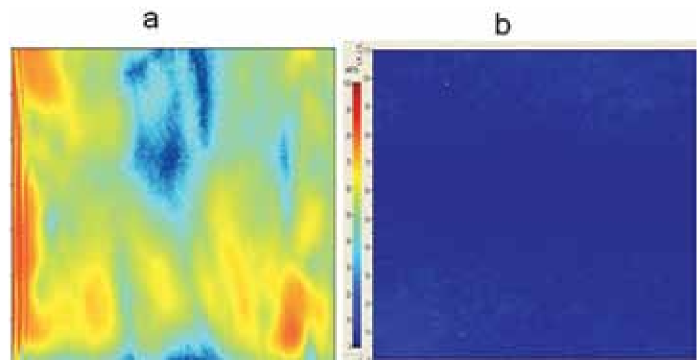

Figure 1. C-scan images of Shoe Upper Weight Crust using (a) 100 KHz and (b) 200 KHz frequency transducers.

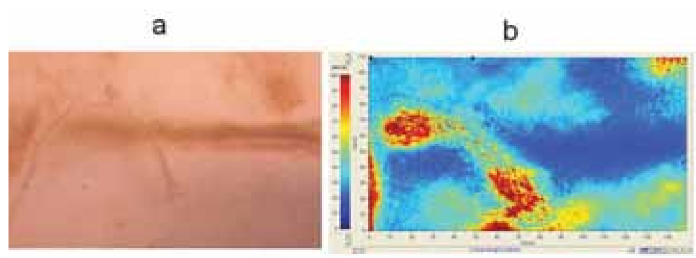

Figure 2. Photo of (a) Crust leather with surface defect and (b) the corresponding C-scan image using 100 kHz transducer.

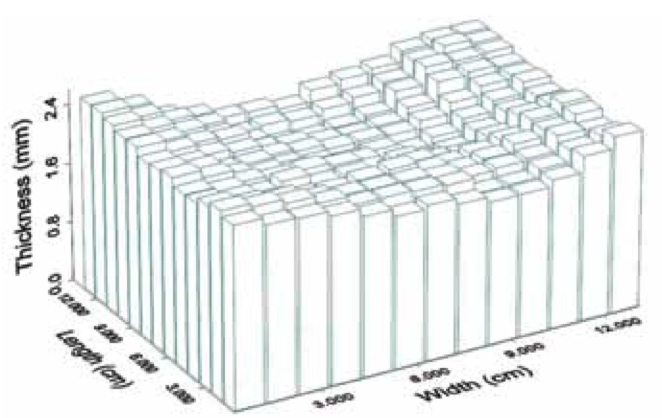

Figure 3. Thickness variation of a crust leather sample used for AU test.

Besides thickness, the gain of AU applied in the test also has a pronounced effect on test results. Figure 4 shows the C-scan images tested at different levels of gain: -10, -5, 0, and 5 dB. These C-scans indicate that amplitude increases significantly as the gain increases; The color changes from blue to red/brown. It appears that a -10 dB gain yields the best test results, giving an image with the most color contrast, representing the variation of thickness.

Figure 5 shows the linear relationship between two amplitude values obtained from -5 and -10 dB gains. Doubling the gain resulted in 1.77 times increase in amplitude. Ideally, the amplitude could have doubled when the gain was raised from -10 to -5 dB, however the discrepancy is probably because of thickness variations and the energy loss from the refection of waves when the waves came in contact with the sample surface. Note that at a gain of -5 dB, amplitude reaches a plateau around 100, while the amplitude at -10 dB still has room to climb. Therefore it appears that -10 dB will be the optimal gain needed to apply in the AU test.

Time of flight (TOF) is the travel time (μs) of the sound waves through the test sample. It is reversely proportional to the velocity of sound. It reflects how "smooth" the sound can transmit through the sample, which is governed by the property of materials. Figure 6 shows TOF at various gain levels. There

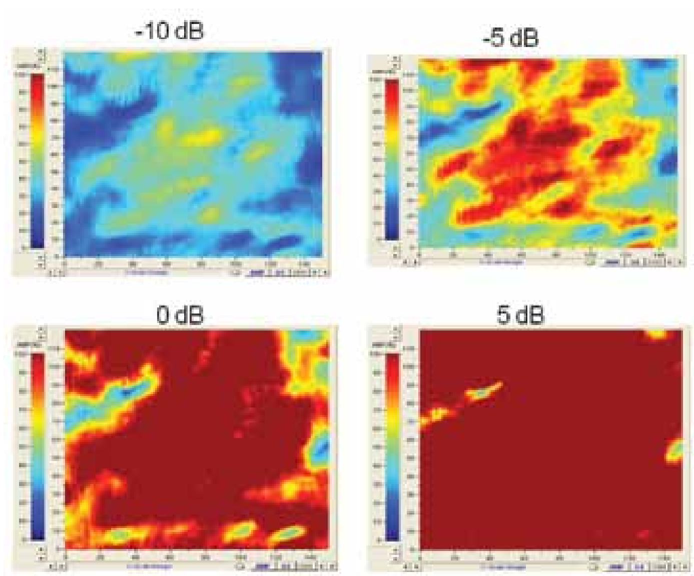

Figure 4. Amplitude varies with AU gain.

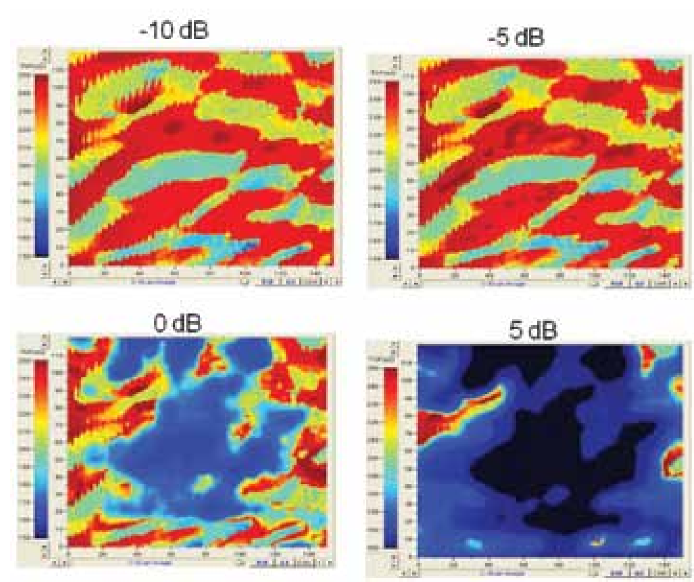

Figure 6. TOF varies with AU gain.

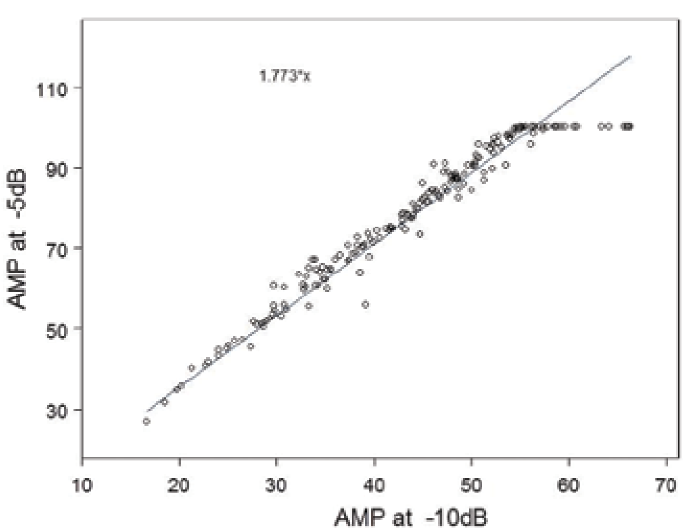

Figure 5. Amplitude proportionally changes with AU gain until it reaches a plateau.

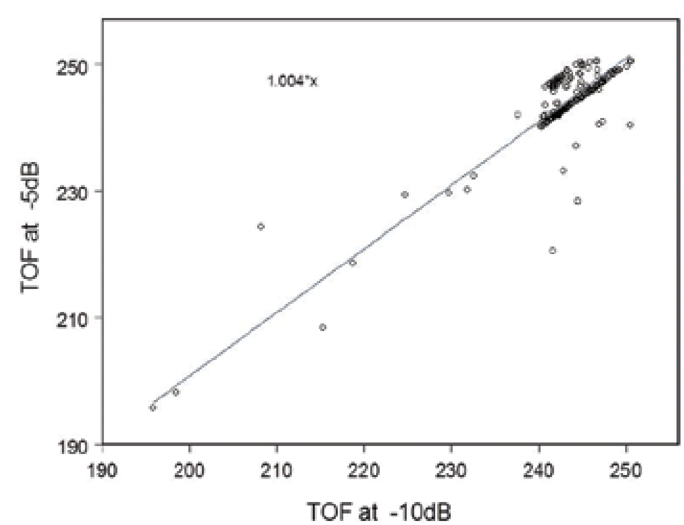

Figure 7. The relationship between TOF at -5 dB and TOF at -10 dB.

is little difference in TOF between -10 dB and -5 dB, whereas more difference between 0 dB and 5 dB. Figure 7 demonstrates the relationship between TOF at -5 dB and TOF at -10 dB. The slope of the regression line is close to 1, indicating that the change between these two TOF values is very little. Within this range of gain (i.e. -5 dB and -10 dB range), the TOF appears to be relatively stable. However, as the gain is increased to 0 dB and 5 dB, the TOF appears to be significantly reduced. When the gain of -5 dB, 0 dB, and 5 dB are compared there is a large difference seen in Figure 6, in which the C-scans are becoming bluer, indicating the transmission time of the pulsing wave through the leather samples is decreasing.

Figure 8 shows a 3-D regression plot of the amplitude (AMP) of transmitted AU waves through samples as a function of thickness of the sample and gain of the instrument simultaneously, where the dots are data points. These data demonstrate that the amplitude of transmitted AU waves increases when either gain increases or sample thickness decreases.

Figure 9 shows the 3-D regression plot of the time of flight (TOF) of transmitted AU waves through samples as a function of the thickness of sample and gain of instrument. It indicates that transmission time through the leather samples decreases when either the gain increases or sample thickness decreases. Both regression equations shown on Figures 8 and 9 are very valuable to estimate the effects of thickness and gain on the amplitude and TOF of transmitted AU waves.

CONCLUSIONS

The objective of this research was to develop an airborne ultrasonic technology to evaluate the quality of hides and leather. The key for success in AU testing is to use AU transducers with low resonant frequencies, which leads an effective transmission of ultrasonic waves through hides or leather. The research results showed the 100 KHz transducer works well for crust leather. This study also showed the AMP and TOF are strongly affected by the sample thickness and instrument gain applied to the AU tests. The results will be instrumental in finalizing the development of AU technology for hides and leather inspections.

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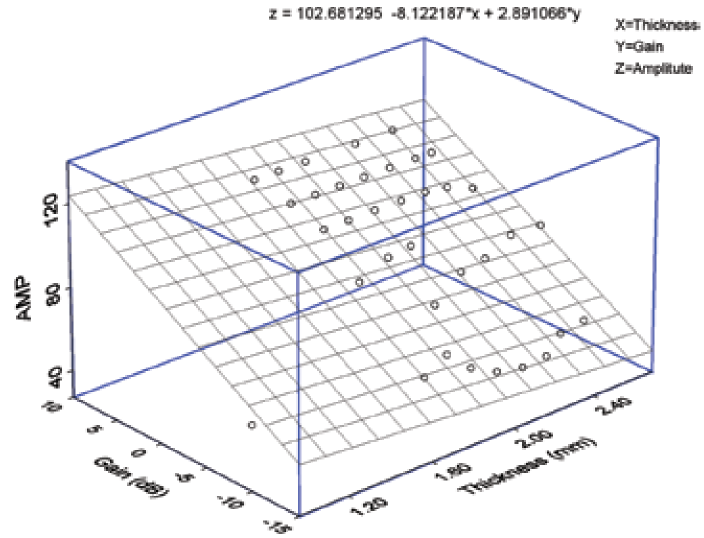

Figure 8. Amplitude as a function of thickness and gain.

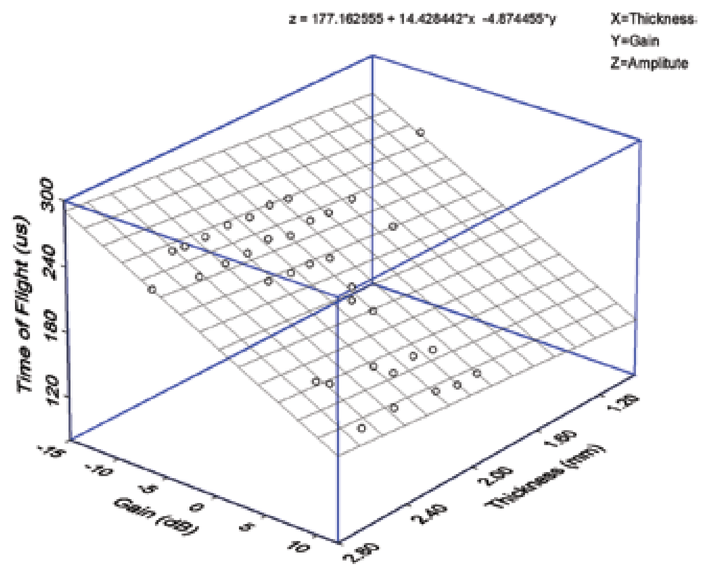

Figure 9. TOF as a function of thickness and gain.

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