The Prediction of Leather Mechanical Properties from Airborne Ultrasonic Testing of Hides

by

Cheng-Kung Liu,* Nicholas P. Latona and Mathew Brady

*United States Department of Agriculture,** Agricultural Research Service, Eastern Regional Research Center,*
600 East Mermaid Lane, Wyndmoor, PA 19038

Abstract

High quality, clean, and well-preserved hides are paramount for competitiveness in both domestic and export markets. Currently, hides are visually inspected and ranked for quality and sale price, which is not reliable when hair is present on the hides. Advanced technologies are needed to nondestructively and accurately characterize the quality of hides and enable one to predict the mechanical properties of leather. Research was carried out to develop airborne ultrasonic (AU) methods to nondestructively characterize the quality of hides that are useful for predicting the mechanical properties of leather. The developed nondestructive method is based on measuring the AU waves transmitted through the hide samples. We performed a systematic study and used a statistical experimental design to establish the relationship between key test parameters and responding AU quantities, thereby establishing proper AU testing methods for hides. Moreover, observations showed AU parameters derived from the distributions of Time of Flight (TOFd) and the amplitude of transmitted waves (AMPd) have a strong correlation with the mechanical properties of leather. This study demonstrated that the tensile strength, stiffness, elongation, and toughness of leather could be nondestructively predicted by the physical quantities obtained from AU testing of hides.

Introduction

Animal hides are the highest value byproducts of the meat industry. The U.S. beef industry produces approximately 32 million cattle hides annually. Nearly 90% of the cattle hides are exported for processing to countries with lower labor costs and less restrictive environmental policies. The export market for raw and wet blue hides is currently valued at more than $2.8 billion annually. High quality, clean, and well-preserved hides are important for competitiveness in both domestic and export markets.

The quality and sale price of hides are commonly determined by visual inspection as well as other factors, such as weight. However, when hair is present, hides cannot be effectively ranked, and can lead to disputes over fair price. Therefore, development of an objective and nondestructive method to accurately characterize the quality of hides is needed. This research aims to develop an advanced technology to provide greater precision in quality identification prior to tanning, which will place U.S. hides and skins in a competitive advantage in the global marketplace over other national competitors.

Airborne Ultrasonic (AU) methods have been used extensively in the inspection of lumber and composites.[1-5] With appropriate AU equipment, one can perform reliable inspections for defects such as voids, cracks and disbonds in a wide variety of water-incompatible materials. A variety of AU frequencies can be used, allowing optimization for resolution or penetration. The timber industry was among the first that employed AU commercially.[3,6] On the other hand, composite materials, particularly within the aerospace industry, have been a primary area of application for AU methods.[2,7] These are all through transmission C-scans examples, which will be reasonably familiar to users of conventional ultrasonics.

We were the first to develop AU methods to detect leather defects and characterize its quality such as tensile strength and stiffness.[8-9] As this is a non-contact technique, it is an ideal characterization method for large leather or hides. The AU sensor is designed for dynamic measurements and offers several key advantages in automated and moving process applications. Airborne ultrasonic testing involves pulsing ultrasonic signals at the material and measuring the reflected amplitude of those signals emanating from the material.[9] The amplitude of ultrasonic signals reflected at the surface of a planar material (such as films, sheets, fabrics, and leather or hides) is a function of the material's surface morphological variations. Therefore defects, such as scars, insect bites, or knife cuts should be able to be detected because they

*Corresponding author e-mail address: ChengKung.Liu@ars.usda.gov; Tel (215) 836-6924
Manuscript received October 3, 2016, accepted for publication November 1, 2016.
**Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture (USDA). USDA is an equal opportunity provider and employer.

will change the intensity of the AU signal reflecting from the surface of the material. Our studies indicated that AU testing could reveal the presence of defects in leather or any other physical discontinuity, which could affect the leather quality. The important leather quality such as tensile strength and stiffness showed good correlation with AU data so that those properties could be estimated from AU testing.

Our recent AU testing involves pulsing ultrasonic waves and measuring the amplitude of those waves transmitted through the material.[10-13] We believe by using the through transmission mode, more useful information can be extracted from the AU scan than the reflective mode, particularly for hides, which are covered by hair. When performing AU testing, 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, selection 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.

In AU testing, ultrasonic waves travel from one medium to another (for example, from air to leather), a large portion of that energy is reflected and the remaining energy is transmitted. The physical quantity that governs the reflected and transmitted relationship is referred to as acoustic impedance $(Z) = (\rho E)^{1/2}$, where ρ is the density of medium, E is the elastic constant of medium.[14] This square-root relationship indicates the acoustic impedance of a material and is governed by its density and elasticity. 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 as the acoustic reflection coefficient (R), which equals $(Z_1-Z_2)^2 / (Z_1+Z_2)^2$, where Z_1 is the acoustic impedance of medium 1 and Z_2 is the acoustic impedance of medium 2. The higher the R value, the greater the percentage of energy will be reflected at the interface or boundary between one medium and another. Therefore, it is predictable that the mismatch of acoustic impedance weakens the ultrasonic wave transmission. Defects such as voids, insect damage, and brands will change R% and consequently affect the amplitude or time of flight of the wave transmitted through the material, which will show up in AU images such as C-scans.

Our previous studies indicated that the key for success in AU testing for soft materials such as hides and leather is to use AU transducers with frequencies below 200 kHz, which leads an effective transmission of ultrasonic waves through samples.[10-13] The variations in 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, which existed in the samples. To perfect AU methods for hides and leather inspections, 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.[12] The research results showed the 100 kHz transducer works well for crust leather. This study also demonstrated 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 characterizing the quality of hides. Observations showed that the tensile strength, stiffness, fracture energy, and grain break of leather could be measured nondestructively by using the AU methods described in an earlier report.[13] Moreover, the grain break of leather, which is very time-consuming to determine and often subjective between different operators, has been shown to be predictable using this nondestructive method, potentially making it a more quantitative measurement instead of a subjective measurement between operators.

In this report, we discuss our research findings for the effects of test parameters on the AU testing of raw hides using lower frequency transducers, 50 kHz, compared to that previously reported.[12] We performed a systematic study and used a statistical experimental design to establish the relationship between key test parameters such as instrument gain, distance of transducers (between the transmitter and receiver with the sample in the middle) and responding AU quantities, thereby establishing proper AU testing methods for hides. We also investigated the relationship between AU quantities of hides and mechanical properties of leather that was tanned from the tested hides. We discovered two AU physical quantities from testing the hides that if used jointly showed good correlation with the mechanical properties of leather. The derived regression equations are applicable for the estimation of leather mechanical properties based on the AU testing of hides, which would be useful in a grading system.

Experimental

The AU test system consisted of two ultrasonic transducers, a transmitter (model: NCG50-D38, the Ultran Group, State College, PA) with a diameter of 38 mm pulsed with a tone burst through a power amplifier, and a receiver (model: NCG50-D38) with the same size as transmitter 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 taught across a frame with two parallel bars in order to minimize any slack in the sample.

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 (Time of Flight) 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.[11] The A-scan presents the waveform of the received signal and gate 1 is set to the first waveform, whereas gate 2 is set to the second waveform . Converting C-scan images into numeric data is the key step to enable one to quantitatively determine the correlation with other materials properties. The resolution of the scan or data collection sensitivity was set to 0.5 mm and the index or advancement of the sensor was set to 0.5 mm. Time of Flight (TOF) values were recorded in the UTWIN software, where the TOF represents the time it took to reach the maximum peak in the defined gate or period of time. A distribution of the TOF values (TOFd) from 100 to 250 µs were set as gate 1 in the software to collect the first waveform. The recorded values are a percentage of the waves that reached the maximum peak in increments of 10 µs. Gate 2 was set from 210 to 300 µs and gate 3 from 310 to 500 µs, in which the percentage of the maximum amplitudes (AMPd) in increments of 10% were also recorded. An Insight-5 test frame and Testworks-4 data acquisition software (MTS Systems Corp., Minneapolis, MN) were used throughout this work. Mechanical properties including tensile strength, elongation, Young's modulus, and fracture energy (toughness) were tested as described in a previous paper.[15] All samples were tested in a conditioned room set at 20 ± 2°C and 65 ± 5% RH.

Experimental Design

To establish an AU test system, it is very important to understand the effects of key test parameters on the testing results of AU quantities. In this study, three key variables are instrument gain, distance of AU between emitter and receiver transducers, and AU frequency set for AU testing. For a systematic investigation, it will be very desirable to present the results in a mathematical form that precisely describes the relationship between variables and responses. We therefore applied a statistical experimental design technique to establish regression models. As shown in Table I, a central composite design was used to arrange experimental conditions, thereby establishing regression models. This experimental design was developed by Box and Hunter and is widely used for fitting a second-order model.[16] A comprehensive description for this type of experimental design was given by Cochran and Cox.[17] The three factors selected in the current study were the gain (X_1), distance between wave transmitter and receiver (X_2), and frequency (X_3). A regression model was derived having the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products (CP) as shown in Equation 1. The regression coefficients along with analysis of variance (ANOVA) can be obtained readily using statistical software with a microcomputer. For the sake of easy calculation and simplifying the regression equations, the variables X_i were coded (transformed) from X_i' with original scales. The levels of the coded variables X_1, X_2, and X_3 were obtained by means of the formulae: $X_1 = (X_1' - 10)/10$, $X_2 = (X_2' - 3)/1$, and $X_3 = (X_3' - 50)/20$, where X_1', X_2', X_3' are the variables with original scales (as listed in Table I). For better understanding the results of an investigation, it is extremely instrumental to visualize the relation between the response (dependent variable) and the factor (independent variable) levels geometrically. Response surfaces (a surface plot of resultant property as a function of multiple independent variables) were constructed based on the regression equation, using a graphics and data analysis software "Axum" version 6 developed by MathSoft, Inc, Cambridge, MA.

Results and Discussion

A typical A-scan (1a) and C-scan (1b and 1c) are demonstrated in Figure 1. In this study the c-scan using Amplitude (Figure 1b.) did not provide enough information as the Time of Flight (TOF) values (Figure 1c.) and therefore TOF was used in this study. TOF distribution values (TOFd) were recorded in the UTWIN software, which represent the percentage of waves that reached the maximum amplitude from gate 1 set to 100 to 250 µs in increments of 10 µs. The TOFd from 100 to 500 µs was recorded also in increments of 10 µs. The distribution values for gate 1 and the other statistical values were calculated by the UTWIN software.

From ANOVA, as shown in Table III, we concluded that the TOFd at gate 1 (from 130 to 140 µs) yielded the best correlation with the three key test variables as shown in Table II. The corresponding regression model is listed as follows:

$$Y = 25.5731 - 9.0509 X_1 + 0.8009 X_2 - 4.3739 X_3 - 0.5244 X_1^2 - 0.6335 X_1 X_2 + 5.3709 X_1 X_3 + 0.4377 X_2^2 - 2.9748 X_2 X_3 - 2.4258 X_3^2 \quad (1)$$

The multiple correlation coefficient[10] (R) for this quadratic model is 0.90; it is evident that the quadratic model fits the data fairly well. On the other hand, observation also showed the Amplitude distribution value (AMPd) at gate 2 (from 20 to 30%) yielded the second best correlation with the three key test variables as shown in Table IV. The corresponding regression model is listed as follows:

$$Y = 28.1526 + 0.4298 X_1 - 0.4570 X_2 + 0.4995 X_3 - 3.3232 X_1^2 - 0.4478 X_1 X_2 + 0.4362 X_1 X_3 + 0.4377 X_2^2 - 0.4284 X_2 X_3 - 3.2801 X_3^2 \quad (2)$$

Figure 2 is a 3-D plot of the response surface of TOFd as a function of frequency and AU gain according to Equation 1, using the graphics and data analysis software Axum version 6 developed by MathSoft, Inc, Cambridge, MA. It demonstrates that the TOFd decreases with an increase in instrument gain. Figure 2 also clearly shows that TOFd decreased significantly as frequency increases. TOFd is related to the time needed to pass through the sample, if gain increases, it is reasonable to expect the time to the maximum peak will shorten and consequently TOFd decreases due to increasing the sensitivity of the software and making the waveform bigger. For a similar reason, frequency increases will lead to more AU energy generated within the waves, thereby speeding up the transmission of sound waves resulting in a lower TOFd.

Table I
Experimental Plan

Run	Coded Values			Actual Value		
	X_1	X_2	X_3	X_1'	X_2'	X_3'
	Gain	Distance	Frequency	Gain (dB)	Distance (cm)	Frequency (kHz)
1	1	1	1	0	2	30
2	1	1	1	0	2	70
3	1	1	1	0	4	30
4	1	1	1	0	4	70
5	1	1	1	20	2	30
6	1	1	1	20	2	70
7	1	1	1	20	4	30
8	1	1	1	20	4	70
9	1.682	0	0	-6.8	3	50
10	1.682	0	0	26.8	3	50
11	0	1.682	0	10	1.3	50
12	0	1.682	0	10	4.7	50
13	0	0	1.682	10	3	16.4
14	0	0	1.682	10	3	83.6
15	0	0	0	10	3	50
16	0	0	0	10	3	50
17	0	0	0	10	3	50
18	0	0	0	10	3	50
19	0	0	0	10	3	50
20	0	0	0	10	3	50
21	0	0	0	10	3	50
22	0	0	0	10	3	50
23	0	0	0	10	3	50

Figure 3 shows a 3-D plot of the response surface of TOFd as a function of transducer distance and frequency according to Equation 2. It demonstrates that the TOFd increases with an increase in transducer distance. This is probably due to a longer wave path with an increase in the distance of the transducers, thereby causing TOFd increases. Figure 3 also clearly shows that TOFd slowly increases as frequency increases until it reaches 80 kHz. This could also be due to the peak frequency of the transducers is 60 kHz, and as the frequency is raised past its peak the intensity of the waves, consequently TOFd decreases.

The second part of this research is to investigate the relationship between AU physical quantities measured from hides and the mechanical properties of correspondent leather tanned from such hides. Figure 4 shows a 3-D regression plot of tensile strength as a function of TOFd and AMPd simultaneously, where the dots are data points. It shows the tensile strength has a strong positive correlation with TOFd, whereas with the AMPd the tensile strength has only a small positive correlation. The reason for this difference is ascribed to the leather structural

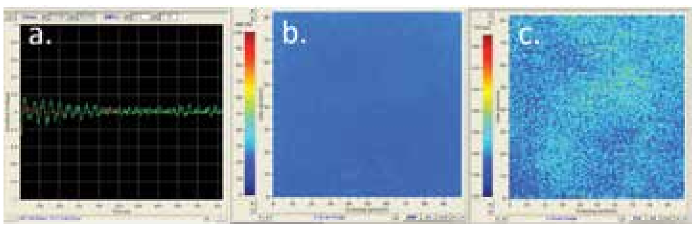

Figure 1. Pictures A- Scan (a.), C-scan with Amplitude as Y-axis (b.) and C-scan with Time of Flight as Y-axis (c.) for one of the control samples.

Table II
Response Surface Regression for TOFd at gate 1 versus X_1, X_2, and X_3
Estimated Regression Coefficients for TOFd

Term	Coefficient	SE Coef (The standard error of the coefficient)	T-value	P-value
Constant	25.5731	3.791	6.749	0.000
X_1	-9.0509	1.831	-4.943	0.000
X_2	0.8009	1.831	0.437	0.669
X_3	-4.3739	1.831	-2.389	0.033
X_1^2	-0.5244	1.009	-0.519	0.612
X_2^2	0.4377	1.009	0.434	0.672
X_3^2	-2.4258	1.009	-2.403	0.032
X_1X_2	-0.6335	1.423	-0.445	0.663
X_1X_3	5.3709	1.423	3.776	0.002
X_2X_3	-0.4284	2.110	-0.203	0.842

Table III
Analysis of Variance for TOFd (130-140 µs) at gate 1 versus X_1, X_2, and X_3

Source of Variation	DF	SS	MS	F-value	P-value
Regression	9	7173.7	797.08	6.15	0.002
Linear	3	3928.1	1309.35	10.11	0.001
Square	3	807.4	269.14	20.8	0.153
Interaction	3	2438.2	812.73	6.28	0.007
Residual Error	13	1683.6	129.51		
Lack of Fit	5	1508.1	301.62	13.75	0.001
Pure Error	8	175.5	21.94		
Total	22				

Table IV
Response Surface Regression: AMPd at gate 2 versus X_1, X_2, and X_3

Term	Coefficient	SE Coef	T-value	P-value
Constant	28.1526	5.623	5.007	0.000
X_1	0.4298	2.716	0.158	0.877
X_2	-0.4570	2.716	-0.168	0.869
X_3	0.4995	2.716	0.184	0.857
X_1^2	-3.3232	1.497	-2.220	0.045
X_2^2	-3.2861	1.497	-2.195	0.047
X_3^2	-3.2801	1.497	-2.191	0.047
X_1X_2	-0.4478	2.110	-0.212	0.935
X_1X_3	0.4362	2.110	0.207	0.839
X_2X_3	-0.4284	2.110	-0.203	0.842

difference. TOFd is related to the distribution of time of flight, which is increased with 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 the material. The greater amount of TOFd reflects hides dense fibrous structure, which results in a longer transmission time of ultrasonic waves through the hides, therefore it could indicate a stronger leather. However, this principle may not apply to the AMPd, probably because besides density, the AMPd is also affected by the elasticity of the hide fibers. The higher AMPd indicates higher rigidity, which may have some degrees of negative effect on the tensile strength of leather. Importantly, the results demonstrated in Figure 4 imply that the tensile strength of leather can be predicted by the AU nondestructive test method described here, by measuring the TOFd and AMPd of hides. In a variety of applications, leather goods must be capable of resisting considerable stress without fracture, therefore adequate tensile strength is very important in manufacturing leather goods, where the leather is often subjected to a tensile force during mechanical stretching or elongation.

Figure 5 shows a 3-D regression plot of elongation as a function of AMPd and TOFd. Studies showed elongation increased with AMPd and decreased with TOFd; however, as shown in Figure 5, it is affected more by AMPd than by TOFd. Again this shows the AMPd is related to the elasticity of the material, thereby passively affecting the elongation of leather. On the other hand, the TOFd decreased with an increase in elongation possibly due to the denser fiber structure which caused the leather to fracture at lower elongations.

Table V
Analysis of Variance for AMPd at gate 2 versus X_1, X_2, and X_3

Source	DF	SS	MS	F-value	P-value
Regression	9	4149.21	461.02	1.62	0.208
Linear	3	24.84	8.28	0.03	0.993
Square	3	4087.61	1362.54	4.78	0.019
Interaction	3	36.76	12.25	0.04	0.988
Residual Error	13	3704.17	284.94		
Lack of Fit	5	50.14	10.03	0.02	1
Pure Error	8	3654.03	456.75		
Total	22				

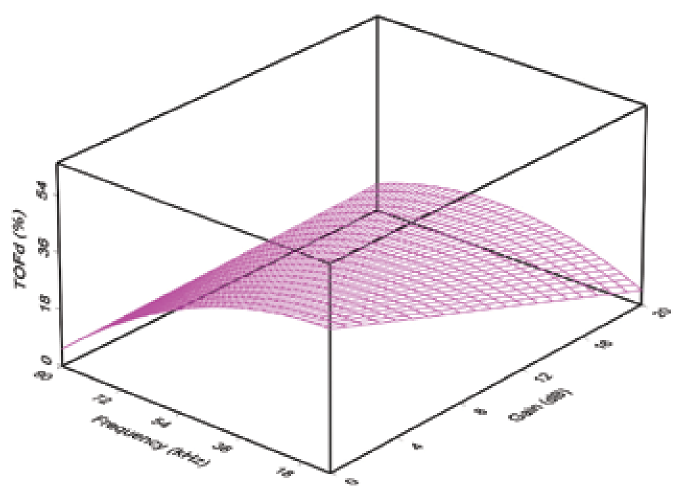

Figure 2. 3-D regression plot of TOFd as a function of AU gain and frequency.

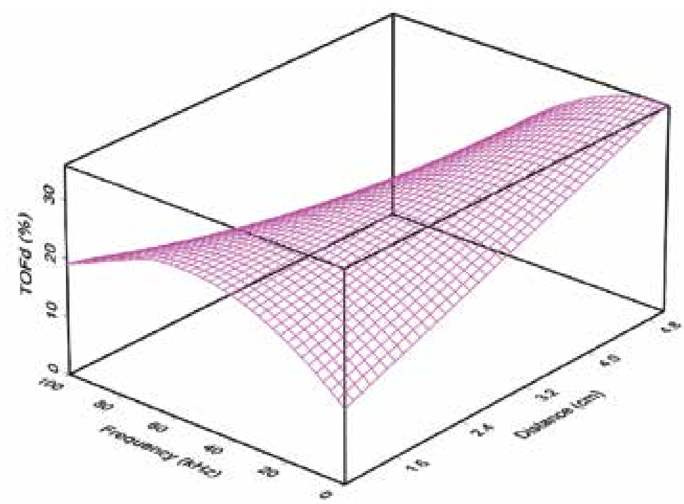

Figure 3. 3-D regression plot of TOFd as a function of distance of transducer and frequency.

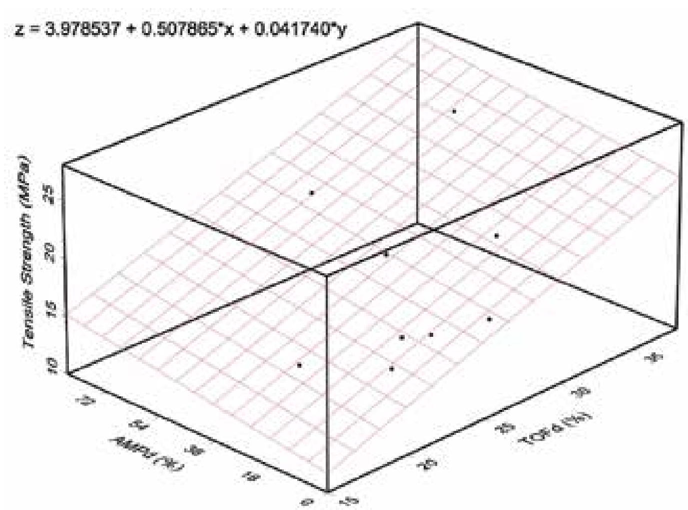

Figure 4. Tensile strength as a function of TOFd and AMPd.

Stiffness

Young's modulus is one of the most important physical quantities characterizing the mechanical properties of leather. It expresses the resistance of leather subjected to a small tensile deformation, and it is commonly known that the higher the Young's modulus, the stiffer the leather is. In fact, its reciprocal has been named compliance in the literature.[19] Young's modulus has been linked to the fine structure of leather, such as the degree of fiber orientation[20-21] and fiber adhesion.[22] It also has been reported that this physical quantity has been associated with leather softness, temper, and handle.[23-25] It has been known to be extremely sensitive not only to changes of composition, moisture, and fatliquor concentration, but also to various leather making processes such as drying and staking.

Figure 6 is a regression plot of Young's modulus as a function of TOFd and AMPd. It shows the Young's modulus has a positive correlation with TOFd but negatively correlates with AMPd. As mentioned before, the greater TOFd value indicates a longer transmission time of ultrasonic waves through the hide samples. This reflects a denser fibrous structure, and therefore stiffer leather, which results in a higher Young's modulus.

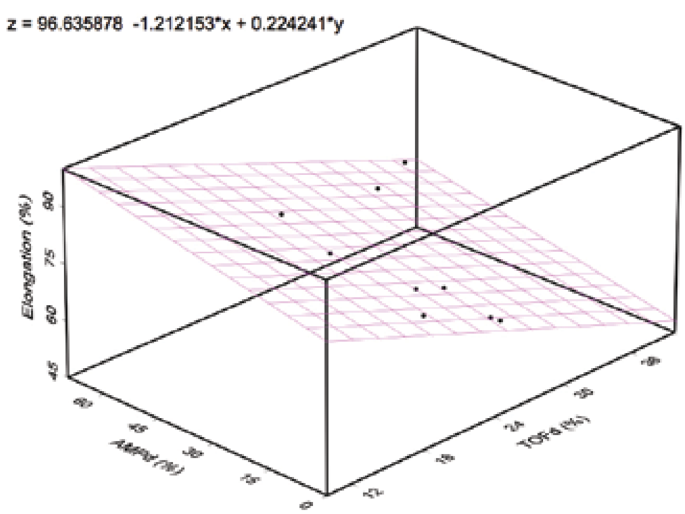

Figure 5. Elongation as a function of TOFd and AMPd.

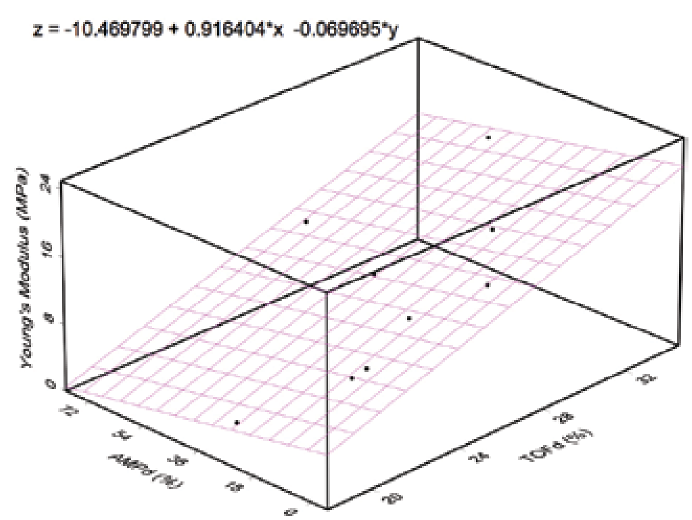

Figure 6. Young's modulus as a function of TOFd and AMPd

Leather Toughness

Toughness has been described in a previous report as a physical quantity determined by measuring the energy required to fracture the leather sample, which is the area under the stress-strain curve.[15] Good toughness reflects a superior balance of strength and flexibility as shown in Figure 7, a regression plot of toughness as a function of TOFd and AMPd, in which both AU quantities have positive effects on toughness.

Figure 8 shows a 3-D regression plot of the thickness as a function of TOFd and AMPd. These data demonstrate that the thickness of leather increases with either TOFd or AMPd. This is probably due to the increase in the thickness of hides which will lead to a longer time for the wave to travel through the sample.

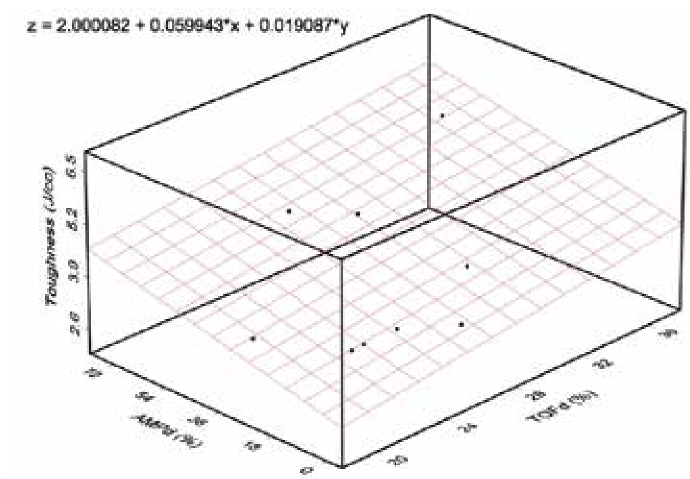

Figure 7. Toughness as a function of AMPd and TOFd.

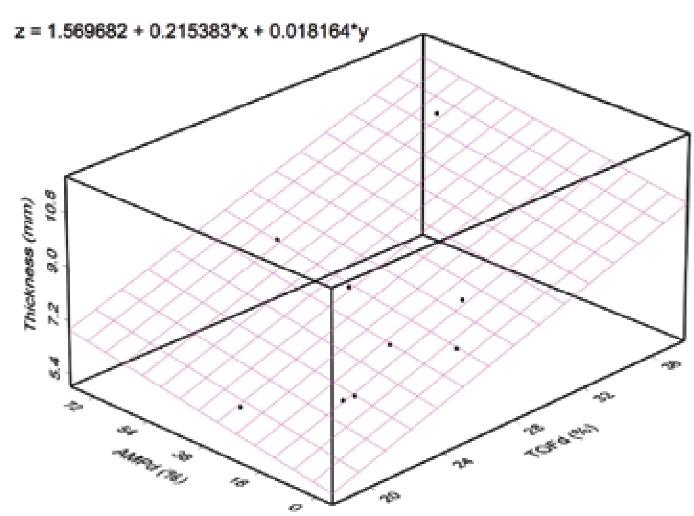

Figure 8. Thickness as a function of TOFd and AMPd.

Conclusions

This report revealed the method using AU to characterize the properties of hides and further to predict the mechanical properties of leather. The developed nondestructive method is based on measuring the AU waves transmitted through the hide samples. In this investigation, we discovered that TOF distribution value (TOFd) at gate 1 (from 130 to 140 µs) yielded the best correlation with the AU test variables. Observations also showed that the tensile strength, stiffness, elongation, and toughness of leather could be predicted by the TOFd and AMPd quantities tested for hides. In conclusion, this research provides the industry with a nondestructive way in which to evaluate the ultrasonic quantities of hides, which in turn enable the prediction the mechanical properties of the leather tanned from those hides.

Acknowledgement

The authors thank Joe Lee and Zerlina Muir of the Eastern Regional Research Center, ARS, USDA for their assistance in sample preparations.

References

1. Hosten, B., Castaings M., Tretout H. and Voilluame H.; Identification of composite materials elastic moduli from Lamb wave velocities measured with single sided, contactless ultrasonic method. *Rev Prog Quant Nondestruct Eval* **20**, 1023-1030, 2001.
2 Rojek, M., Stabik, J., Sokół, S.; Fatigue and ultrasonic testing of epoxy-glass composites. *Journal of Achievements in Materials and Manufacturing Engineering* **20**, 183-186, 2007.
3 Sanabria, S. J., Mueller, C., Neuenschwander, J., Niemz, P., and Sennhauser, U.; Air-Coupled ultrasound as an accurate method for bonding assessment of glued timber. *Wood Sci Technol*, 1-15, 2010
4 Liu, C.-K., Latona, N. P. and Liu, L.S.; Characterizations of biobased materials using acoustic emission methods, pp.138-161. In Kubica, S., Zaikov, G. E. and Liu, L.S.(eds) Biochemical Physics and Biodeterioration New Horizons, Institute for Engineering of Polymer Materials and Dyes, Torun, Poland. 292 pp, 2012.
5 Li, Weili, Coffin, D. R., Jin, T. Z., Latona, N. P., Liu, C.-K., Liu, Bo, Zhang, J., and Liu, L.S.; Biodegradable composites from polyester and sugar beet pulp with antimicrobial coating for food packaging. *J. Applied Polymer Sci.* **126,** E361-E372, 2012.
6 Hsu, D. K., Utrata, D., and Kuo, M. NDE of lumber and natural fiber based products with air coupled. *Review of Quantitative Nondestructive Evaluation,* ed. by D. O. Thompson and D. E. Chimenti, **29**,1533-1540, 2010.
7 Peters, J., Kommareddy, V., Liu, Z. Fei, D., and Hsu, D. (2003) Non-contact inspection of composites using air-coupled ultrasound. *Review of Quantitative Nondestructive Evaluation,* ed. by D. O. Thompson and D. E. Chimenti, **22,** 973-980, 2003.
8 Liu, C.-K, Godinez-Azcuaga, V. F., Latona, N. P., Hanson, M. and Finlayson, R. D.; New acoustic methods for nondestructive evaluation of leather quality. *JALCA* **103**(3), 89-127, 2008.
9 Liu, C.-K, Godinez-Azcuaga, V. F., Latona, N. P., Hanson, M. and Ozevin, D.; Airborne ultrasonics for nondestructive evaluation of leather quality. *JALCA* **103**(7), 209-214, 2008.
10 Liu, C.-K. and Latona, N. P.; Airborne ultrasonic inspection of hides and leather. *JALCA* **106**(11), 326-331, 2011.
11 Liu, C.-K. Latona, N. P., and Yoon, S.-C.; Evaluation of hides, wet blue and leather using airborne ultrasonics. *JALCA* **108**(4), 128-138. 2013.
12 Liu, C.-K. and Latona, N. P. Effects of thickness and gain on the amplitude of airborne ultrasonics. *JALCA* **109**(3), 70-75. 2014.
13 Liu, C.-K., Latona, N. P., and Taylor, M.M., Eble, C., and Ramos, M. L. Characterization of mechanical properties of leather with airborne ultrasonics. *JALCA* **110**(3), 88-93. 2015.
14 Ensminger, D.; Ultrasonic, the low- and high-intensity applications. Marcel Dekker, New York, p.23, 1973.
15 Liu, C.-K. and McClintick, M. D.; An energy approach to the characterization of the fracture resistance of leather. *JALCA* **92**(5), 103-118, 1997.
16 Box, G. E. P., and Hunter, J. S.; Multifactors experimental designs for exploring response surfaces. *Ann. Math. Statist.*, **28**, 1957.
17 Cochran, W. G., and Cox, G. M., Experimental Designs, 2nd ed., Wiley, New York, p. 342, 1957.
18 Bhardwaj, M.; Non-contact Ultrasound - A paradigm shift in our perception and applications of this wave. The Ultran Group, State College, PA, 2012.
19 Morton, W.E., and Hearle, J.W.S.; Physical Properties of Textile Fibers. The Textile Institute, Manchester and London, pp. 272-273, 1978.
20 Kronick, P. L., and Buechler, P. R.; Fiber orientation in calfskin by laser light scattering or X ray diffraction and quantitative relation to mechanical Properties. *JALCA* **81**(7), 221-230, 1986.
21 Kronick, P. L., and Buechler, P. R.; Fiber orientation and small deformation modulus of stretched, partially dried hide. *JALCA* **83**(4), 115-124, 1988.
22 Kronick P L., Page, A., and Komanowsky, M; An acoustic emission study of staking and fatliquor. *JALCA* **88**(5), 178 186, 1993.
23 Guy, R.; A comparison of some foot comfort properties of a full chrome side leather and ‚porvair'. *BLMRA J.* **15**(3), 65 68, 1972.
24 Diebschlag, W.; Measurements of the elasticity of different shoe upper materials as well as their maximum pressure on the foot during walking. *Leder* **26**(1), 7 18, 1975.
25 Tancous, J. J.; Skin, Hide and Leather Defects. Lee Corporation, Cincinnati, pp. 13-14, 1986.