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EXAMINATION OF ASTM D198 TO MONITOR THE ACCURACY OF CALIBRATION OF TIME-OF-FLIGHT ACOUSTICS APPLIED TO TREES

Charles ESSIEN
Forest Products Development Center
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL. USA
E-mail: amankyessien@gmail.com

George CHENG
Forest Products Development Center
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL. USA
E-mail: gcheng@yahoo.com

Osei ASAFU-ADJAYE
Forest Products Development Center
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL. USA
E-mail: oaa0014@auburn.edu

Timothy MCDONALD
Department of Biosystems Engineering, Auburn University, Auburn, AL. USA
E-mail: mcdontp@auburn.edu

Tom GALLAGHER
Forest Products Development Center
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL. USA
E-mail: gallatv@auburn.edu

Becky BARLOW
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36849
E-mail: rjb0003@auburn.edu

Brian K. VIA*
Forest Products Development Center
School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL. USA
E-mail: brianvia@auburn.edu

Abstract:
The use of acoustics for determining tree stiffness can be helpful to improve end product value. However, methods to monitor equipment calibration in the field is limited. This experiment endeavored to test the hypothesis that ASTM D198 is an alternative way to monitor calibration performance in the field. ASTM D198 is a standard test method to test the static modulus of elasticity of structural lumber and is a common test in many local sawmills within the United States. Southern pine lumber (Pinus spp.) was first tested at a local sawmill for modulus of elasticity as per ASTM D198-14. Then acoustic probes were placed 7 feet apart in nominal 2x4 lumber and correlation equations between lumber stiffness and acoustic speed was developed. We then built regression curves for each machine using the lumber derived data, but applied it onto trees. This study found that all three machines gave a statistically equal reading to the reference machine after readjustment with ASTM D198 and supported the hypothesis that the ASTM standard could be an additional monitoring procedure in the field. Meanwhile, we do caution that this standard not be used as a calibration substitution but just as a monitoring check. We feel more studies are warrantied where the log being tested is harvested and converted to small clears or lumber, and then a similar study is performed.

Key words: *acoustics; time-of-flight; tree; stiffness; modulus of elasticity.*

INTRODUCTION

Assessment of tree stiffness is becoming increasingly important as more plantations, with significant portions of juvenile wood, are harvested for lumber and emerging products (Miyamoto *et al.* 2020). Likewise, low density woods are common in some species of faster growth, which can lower final product mechanical properties (Olaoye and Okon-Akan 2020). Non destructive tools for assessment, that has the proper

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* Corresponding author

precision and accuracy, is still lacking (França *et al*. 2020). Acoustics may be one way to classify these materials into the proper stiffness category, but it has been shown that acoustics equipment measures differently than longitudinal free vibration and the traditional universal testing machine (Olaoye 2019). Likewise, there are three types of waves that can occur within the stem: shear wave, Rayleigh wave, and longitudinal wave (Wang and Carter 2015). So caution towards using the method in this paper for straight calibration is warranted and further work is recommended.

While in the academic world, acoustics for trees appears to be frequently researched, our discussions with industry have found the use of this technology to be in its infancy. One reason for the lack of adoption could be due to the absence of accuracy (Olaoye 2019). To complicate matters, between companies and landowners within the supply chain, there can be an absence of confidence in the reading of different machines. Furthermore, the machine may exhibit “wear and tear,” over time in which the measurement drifts from the calibration or the machine will differ straight out of manufacturing (Mochan *et al*. 2009). For example, evidence of differences between acoustic machines became evident, even after the manufacturers calibration bar implied the equipment was properly calibrated (Essien *et al.* 2018).

The acoustic method simply uses the speed of sound between two points. A hammer is used to start the sound wave and a sensor is established at some fixed distance to capture the speed of sound within the woody tissue. Because wood has orthotropic characteristics and natural defects (Jorda *et al.* 2019), it is important to understand how sound will travel between these two points. At the macro scale, the sound will travel along the grain and around knots (Rajeshwar *et al*. 1997). At the cell level for *Pinus taeda,* tracheids are the primary cells with frequent resin canals and pitting; as such, the sound wave will travel along the S2 layer of the cell wall and around pits. Within the S2 layer of the tracheid, the microfibril angle is lowest and this has been shown to vector the sound (Essien *et al*. 2017). At the chemistry level, the elasticity of cellulose has been found to promote faster sound travel while lignin was suggested to insulate the sound around the microfibrils and promote a lower storage modulus (Essen *et al*. 2017; Li *et al*. 2020). The orientation of the tracheids and grain of the wood will further affect the modulus (Stanciu *et al*. 2013). As such, it is important that the time of flight response correlates to strength and stiffness as a function of density, chemistry, knots, and microfibril angle (Newton 2017).

Finally, the ASTM D198 standard tests for the customary modulus of elasticity (MOE) of structural lumber (Irby *et al*. 2020). The test method can be used on lumber or other wood-based products of rectangular cross section. Because this method is considered by most to be a direct measure of MOE, *the objective of this study will be to use ASTM D198-14 as a method for checking the calibration quality of different acoustic machines.*

MATERIALS AND METHODS

Acoustic measurement of trees

Forty trees were randomly sampled from a loblolly pine (*Pinus taeda*) plantation. Acoustic measurements from each machine was taken before and after ASTM D198 adjustment (to be discussed later). The diameter at breast height was measured for each tree. The method of acoustic acquisition on the tree can be seen in Fig. 1. The three different acoustic tools are also described in Fig. 1 and images of these tools can be seen in the dissertation of Essien (2017).

Fig. 1.
Illustration of testing procedure used with the FAKOPP Microsecond Timer (FMT) acoustic tool.

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Each tree was tested with the 4 machines listed in Fig. 2. All of these instruments relied on the common ToF principle (Essien *et al.* 2018). For each machine, the accelerometers (the transmitter and the receiver probes) were positioned on the same side of the tree 120cm apart with the center of the path occurring at breast height. Both probes were positioned 45° to the tree axis and the stress wave was generated by striking the transmitter probe with a steel hammer. Seven readings were taken on each tree and tree velocity was estimated as the ratio of the distance to time. The dynamic modulus of elasticity of the trees was estimated using a common equation (Essien *et al.* 2018). Increment core samples from each tree was taken immediately after ToF measurement to estimate the density using calipers and air-dried weight.

Acoustic measurement of lumber

The same four machines used for the 40 trees were also used for each grade and piece of lumber. Twenty-five pieces of lumber were selected from three grade categories for a total of 75 pieces: machine stress rated (MSR), number 1 (#1), and number 2 (#2) grades respectively. The static MOE was also collected for these lumber pieces using the ASTM D198-14 flexure test method with two point loading. Linear calibration curves were then built between the ToF measurement and D198 determined stiffness. These measurements were also compared to the MSR grade for reference. The calibration correction curves for each machine were then tested on the same 40 trees. A completely randomized design ANOVA was performed to test for differences between the machines before and after calibration adjustment.

RESULTS AND DISCUSSION

Fig. 2 demonstrates the mean acoustic elastic measure for each machine for the same 40 trees. As demonstrated, the machine labeled wt2 and wt3002 were similar to the control; in which, the control had just been calibrated from the manufacturer (AU2). However, our older machine (au3002) over predicts MOE because it needed to be recalibrated for velocity by the manufacturer. What should be noted, is that au3002 came with a metal calibration bar and when tested, the machine appeared to be properly calibrated. This suggests that one should use a wood like small clears or lumber, where the material is analogous to that being tested in the tree.

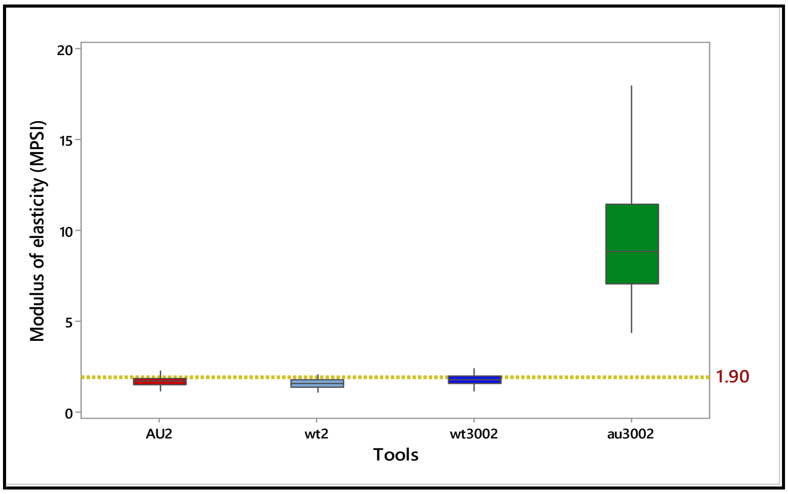
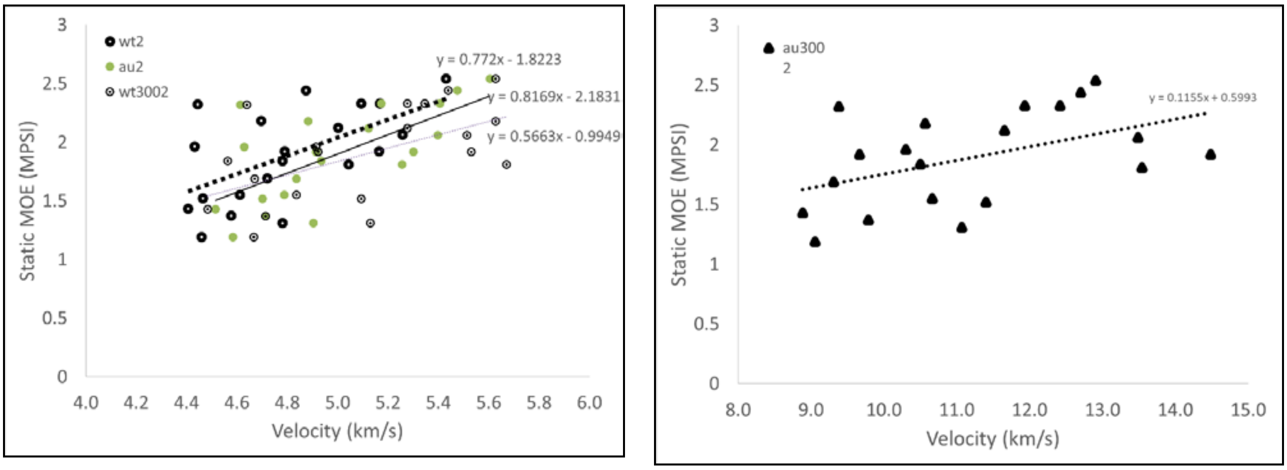


Fig. 2.
Comparison of 4 machines in which a) FAKOPP Microsecond Timer (FMT) acoustic tool (FAKOP Enterprise, Agfalva, Hungary) which was the reference machine (labeled AU2), b) a second FAKOPP Microsecond Timer (FMT) acoustic tool (FAKOP Enterprise, Agfalva, Hungary) that was loaned to the co-PI's (labled WT2). c) Director ST-300 machine loan from a collaborator (labeled Wt3002) b) Director ST-300 machine which was off calibration (labeled Au3002).

Fig. 3 a,b demonstrates the proposed regression curves that will be used to adjust the calibrations shown in Fig. 2. As can be seen, three of the machines exhibited similar performance with one being slightly different based on the smaller slope and intercept (wt30002). As expected, the machine au3002, that was known to be off calibration, exhibited a very different regression trend (Fig. 3b).



a. ***b.***

Fig. 3.
Velocity of each machine versus ASTM D198 determined stiffness for: a) machines that were operating normally as shown in Fig. 2 and b) for au3002 which was known to be off calibration.

The regressions in Fig. 3 was then used to readjust the data for each machine to predict MOE after application of the correction curves to the same 40 trees. As Fig. 4 shows, this lumber based adjustment appeared to show promise for using ASTM D198 as a way to check the calibration of existing equipment. As can be seen, all machines now give the same mean value which supports the hypothesis that the standard could be useful in monitoring calibration quality.

As a possible management plan, it is proposed that a landowner could possibly purchase a batch of lumber that has been tested for MOE through the D198 standard. The landowner would need to determine the appropriate number of lumber pieces (sample size) to test for calibration. Perhaps a limited number of pieces (maybe 10) could be purchased if they represent the low, medium, and high MOE typical for the species being tested. This lumber could then be used periodically to test if calibration quality has changed. Once the calibration has changed, then the machine would need to go through conventional methods to recalibrate.

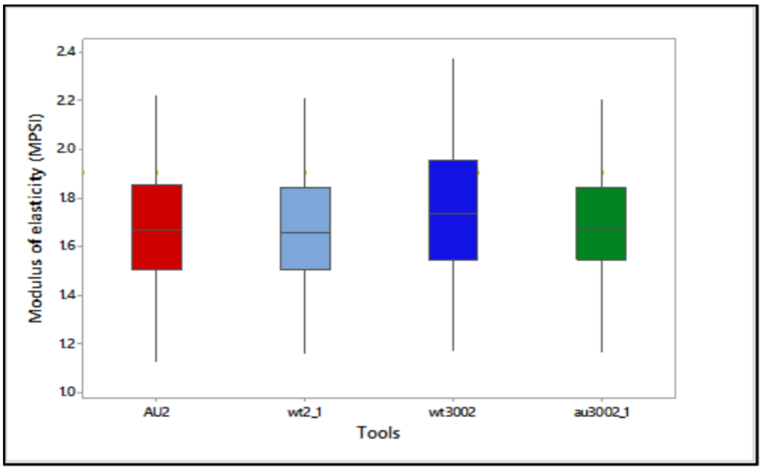


Fig. 4.
Comparison of 4 machines after adjustment with regression equations developed in Fig. 3.

CONCLUSION

This study demonstrated that one can potentially monitor calibration quality acoustic equipment for trees using lumber that has been premeasured for MOE using ASTM D198-14. A possible procedure for quality control monitoring was given for landowners to follow. The adjustment method through regression analysis was given and demonstrated to work for the 40 test trees tested.

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