

EFFECT OF TEMPERATURE ON ACOUSTIC EVALUATION OF STANDING TREES AND LOGS: PART 2: FIELD INVESTIGATION

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Abstract. The objectives of this study were to investigate the effect of seasonal temperature changes on acoustic velocity measured on standing trees and green logs and to develop models for compensating temperature differences because acoustic measurements are performed in different climates and seasons. Field testing was conducted on 20 red pine (*Pinus resinosa*) trees and 10 freshly cut red pine logs at a 45-yr-old plantation stand in Arena, WI. Acoustic velocities of the red pine trees and logs and the ambient temperatures were monitored for 12 consecutive months. Results indicated that ambient temperature had a significant effect on acoustic velocities of trees and logs in winter when temperatures were below the freezing point. Acoustic velocities increased dramatically as ambient temperature dropped to below 0°C, but the increase became less significant when the temperature decreased to below −2.5°C. Above the freezing point, acoustic velocities were less sensitive to ambient temperature changes. From a practical standpoint, acoustic velocities of trees and logs measured at different climates and seasons can be adjusted to a standard temperature if measurements are conducted well above or well below freezing temperatures. However, measurements conducted around freezing temperatures could cause complications in making temperature adjustments. Users should avoid conducting field acoustic testing when wood temperature is around the freezing point.

Keywords: Acoustic velocity, ambient temperature, logs, wood temperature, standing trees.

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INTRODUCTION

Previous research has proven the ability of acoustic wave propagation methods to evaluate wood and fiber quality in trees and logs in field settings (Wang 1999; Huang 2000; Wang et al 2001, 2007a, 2007b). More recent commercial availability of field-ready tools has brought the operational assessment of acoustic velocity as a measure of stiffness into forest management and log and lumber processing sectors of the industry (Wang et al 2007a; Carter 2011). Using these tools allows significant product value to be captured through better decision-making, allocation of resource to highest value uses, and application of best processing methods dependent on log-by-log measures. Because commercial acoustic equipment is implemented in the field for such applications, one has to consider the influence of environmental temperature on acoustic velocity, which is a key parameter for wood property prediction.

Depending on geographic locations and timing of forest operations, trees and logs might be acoustically tested and evaluated in different climates or seasons. Wood temperature of trees and logs at the time of testing could range from above 30°C to well below freezing. Previous studies on small wood samples and structural lumber suggest a direct effect of temperature on acoustic properties of wood. Observed effect of temperature on acoustic velocity in wood below FSP agreed with generally accepted information on this subject, but conflicting results were reported for wood above FSP when wood temperature transitioned from above freezing to below freezing. There are limited data showing the effect of temperature on acoustic velocity of wood measured on standing trees and logs. Little is known about the effect of seasonal temperature changes on acoustic evaluation of standing trees and freshly cut green logs. This information is important to field operations when acoustic technology is used to assess the quality and value of logs, trees, and stands.

Our laboratory study on red pine (*Pinus resinosa*) small clear specimens showed a significant change in acoustic properties of wood as wood tem-

perature changed from -45 to 35°C (Gao et al 2012). A dramatic shift in acoustic velocity and energy loss was observed when wood temperature changed to above or below the freezing point. The objectives of this study were to further investigate effects of environmental temperature on acoustic wave velocity of wood in standing trees and freshly cut logs and to develop analytical models for adjusting tree/log velocity data to account for temperature differences when acoustic measurements are performed in different climates or seasons.

MATERIALS AND METHODS

Test Sites and Samples

The field test site of this study was located in Arena, WI (lat. 43°9'57" N, long. 89°54'26" W). Wisconsin has a humid continental climate, characterized by variable weather patterns and a large seasonal temperature variance. Winter temperatures can be well below freezing, with moderate to occasionally heavy snowfall, and high temperatures occur in summer.

A total of 20 red pine (*Pinus resinosa*) trees were randomly selected from a 45-yr-old plantation stand and acoustically tested through a 1-yr monitoring cycle. The diameter at breast height of the tree samples ranged from 19.4-30.6 cm. Also, we cut down three red pine trees at this site to obtain 12 3.1-m-long log samples. The small-end diameter of the log samples ranged from 18-30 cm. The ends of the log samples were immediately coated with Anchorseal (end sealer for logs and lumber; Anchor-Seal, Inc., Gloucester, MA) after cutting to maintain moisture.

Field Measurements

The field acoustic monitoring process was started in December 2009 and completed in December 2010 (12 consecutive months) (Fig 1). The parameters measured included ambient temperature, internal wood temperatures, acoustic velocities of the trees and logs, and log moisture content. Measurement frequency was once or twice a month, depending on weather conditions.



Figure 1. Field acoustic measurement on standing red pine (*Pinus resinosa*) trees.

Temperature monitoring. To monitor ambient temperature and internal wood temperatures of a tree at the test site, we installed nine thermocouples on a selected tree sample (Tree No. 5). Figure 2 shows the layout of the thermocouple wires installed on the tree trunk, approximately at breast height. To measure

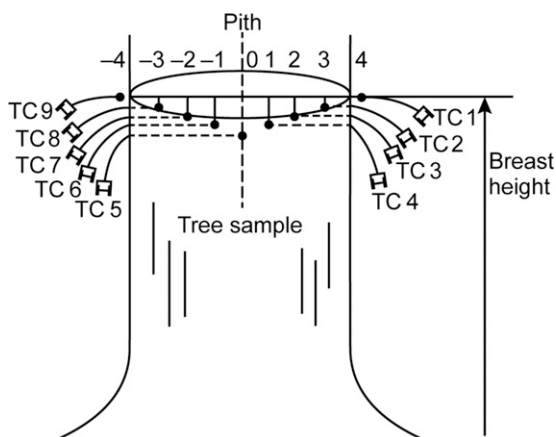


Figure 2. Thermocouple wires inserted into cross section of red pine (*Pinus resinosa*) tree trunk (tree sample No. 5).

internal wood temperatures, seven thermocouples (No. 2 to No. 8) were inserted into the trunk to four different depths (44, 89, 140, and 144 mm [pith]). The other two thermocouples (No. 1. and No. 9) were attached on the trunk's surface to measure ambient temperature. During each field testing, a digital thermometer (HH82A; Omega Engineering, Inc., Stamford, CT) was used to collect temperature data both before and after acoustic measurements. An average temperature was then used to represent the temperature condition of the acoustic testing. The freshly cut log samples were laid down on the forest floor at the test site. They were buried under snow throughout most of the winter because of heavy snowfall. During log testing, we used a noncontact infrared thermometer (Fiber-gen Instruments Limited, Auckland, New Zealand) to measure surface temperature of the log end for each log sample.

In addition to measuring temperatures of logs and trees, we installed a temperature/RH data logger (HOBO Pro RH/Temp H8-032-08; Onset Computer Corporation, Bourne, MA) at the test site to record both ambient temperature and RH data as continuous monitoring throughout the field testing period. Data were downloaded at the middle and end of the monitoring cycle.

Log moisture content monitoring. To monitor moisture content change during the 1-yr testing cycle, we used one additional log as a moisture content sample. Each time after acoustic measurements, we cut a 40- to 50-mm-thick disk from this log sample. The disk was immediately put into a plastic bag to prevent moisture loss. In the meantime, the cut end of the log was again coated with Anchorseal to maintain moisture. Moisture content of each disk was then determined using the oven-dry method according to ASTM (2003).

Acoustic measurements on trees. Acoustic measurement was conducted on each tree sample in the longitudinal direction (along the trunk). A Director ST300 tool (Fiber-gen Instruments Limited) was used to measure the velocity of acoustic waves propagating along the tree trunk

(hereafter referred to as acoustic velocity) (Fig 1). Two probes, one a transmitter and the other a receiver, were driven through the bark at a 45° angle into the outer wood, vertically aligned along the trunk and roughly 1.2 m apart. The transmitter was placed in the lower position about 0.5 m above the ground. The distance between the fixed probes was measured exactly by a laser-guided ultrasound rangefinder built within the ST300 tool. An acoustic wave was initiated and sent into the tree when a hammer hit the transmitter probe. The receiver probe picked up the acoustic signal passing through the tree and determined the time of flight (TOF) of the acoustic waves. The distance, TOF, and calculated velocity could be read directly from a PDA (personal digital assistant) (Carter et al 2005). An average acoustic velocity value was obtained from three sets of measurements for each tree.

Acoustic measurement on logs. Log acoustic velocity was measured using a resonance-based acoustic tool, Director HM200 (Fiber-gen Instruments Limited). Acoustic measurement was conducted by pressing the sensor head against a

log end and striking the same end with a hammer. A weighted acoustic velocity of the log was obtained through analyzing many acoustic pulse reverberations in the log using a built-in fast Fourier transformation program (Harris et al 2002). For each temperature condition, we obtained five velocity readings on each log sample, and an average log velocity was used for the analysis.

RESULTS AND DISCUSSION

Seasonal Temperature Changes

Based on the data logger record, ambient temperature at the test site ranged from -27.8 to 33.9°C during the 1-yr monitoring period with a maximum 61.7°C seasonal temperature difference. At the time of field testing, the lowest temperature observed was actually -10.8°C (in February) and the highest temperature observed was 30.4°C (in July) with a maximum 41.2°C temperature difference. Observed and recorded extreme temperatures differed because field testing was conducted during the daytime, mostly in the morning, whereas the lowest temperatures often occurred during nighttime.

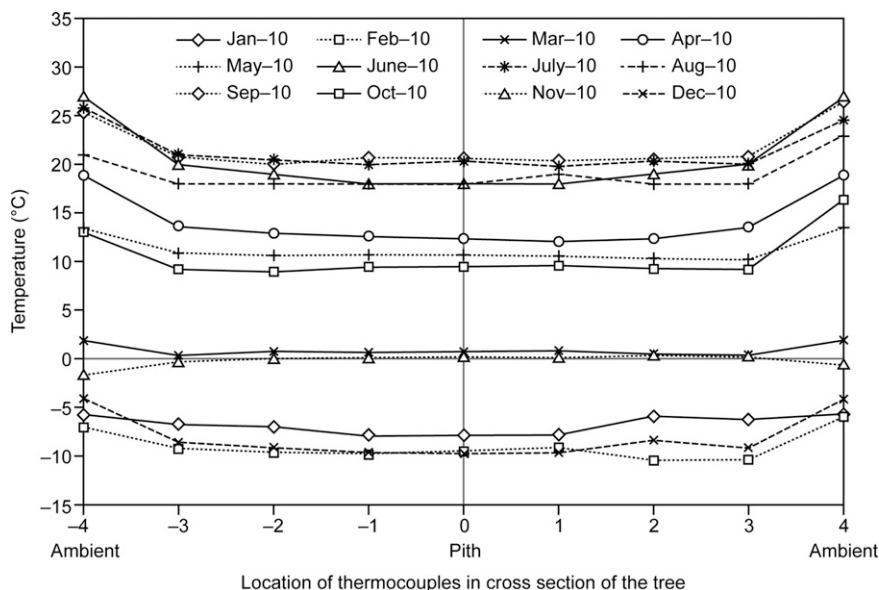


Figure 3. Temperature profiles of trunk cross-section observed in tree sample No. 5 (locations 4, -4 represent ambient air outside the bark).

Temperature Profile of Tree Cross-Section

Figure 3 shows the temperature profiles of the trunk cross-section of Tree No. 5. Wood temperatures were found relatively constant across the diameter of the tree trunk and generally lower than the ambient temperature at the time of testing (morning in this case). The difference between wood temperatures and ambient temperatures ranged from 1 to -8.5°C with an average difference of -3.3°C . We found that wood temperature of the tree responded to ambient temperature changes. Wood temperature linearly increased with ambient temperature increase (Fig 4), but wood temperature change lagged behind the change of ambient temperature. The wood temperature observed throughout the 1-yr period ranged from -9.7°C in February to 21.8°C in July with a maximum seasonal wood temperature change of 31.5°C .

Trends of Acoustic Velocity in 1-Yr Cycle

Figure 5 shows trends of acoustic velocities of the trees and logs during the 1-yr monitoring period. The boxes show the mean acoustic velocities of the trees and logs monitored, and the error bars represent ± 1 standard deviation (SD) of the velocity. The line curves in the plot

demonstrate ambient temperature changes during the acoustic monitoring period. In April, acoustic velocity data of the trees were not obtained because of an equipment breakdown.

At the initial measurement in December 2009 (ambient temperature was 0°C , wood temperature was 1.7°C above freezing), acoustic velocity of the tree samples ranged from 3.715–5.026 km/s with a mean value of 4.266 km/s and acoustic velocity of the log samples ranged from 2.310–3.230 km/s with a mean value of 2.858 km/s. Under the same ambient temperature condition, average acoustic velocity of the trees was significantly higher than average velocity of the logs. This observation is consistent with previous findings (Wang et al 2001, 2007b; Carter et al 2005; Mora et al 2009). The fundamental cause of this deviation was the different wave propagation mechanisms of the two acoustic measurement approaches: TOF method in trees and resonance method in logs (Wang et al 2007b; Wang 2011). A secondary cause was that TOF measurement on trees was more influenced by the mature wood zone in the tree trunks than the weighted acoustic velocity of logs obtained through analyzing many acoustic pulse reverberations (Chauhan and Walker 2006; Grabianowski et al 2006; Mora et al 2009).

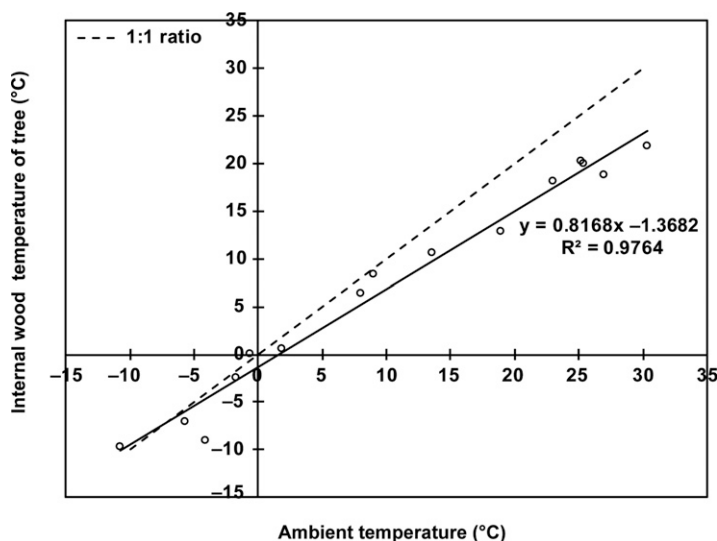


Figure 4. Internal wood temperature of red pine (*Pinus resinosa*) tree in relation to ambient temperature.

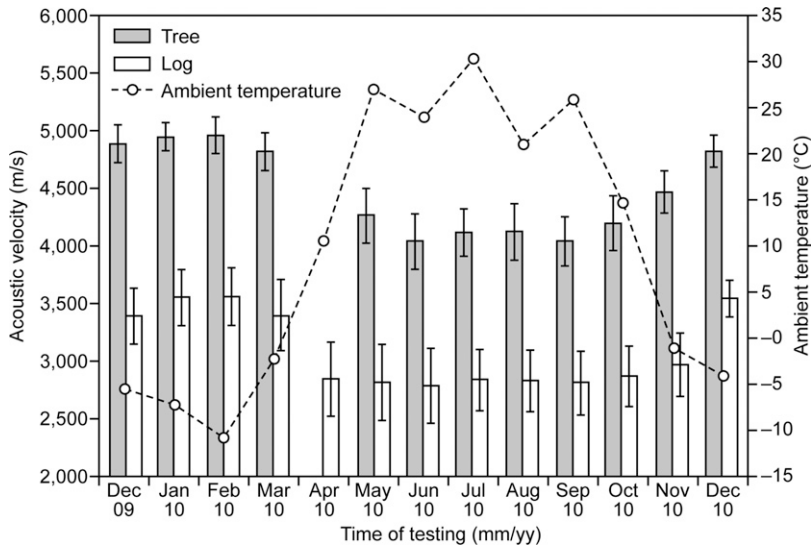


Figure 5. Trends of acoustic velocities of red pine trees (*Pinus resinosa*) and logs during a 1-yr period.

The main purpose for collecting field acoustic data in this study was to determine the effect of seasonal temperature changes on acoustic velocities of trees and logs. Therefore, the results and discussion presented are based on the mean acoustic velocity values.

For both trees and logs, acoustic velocities were found relatively constant from spring to fall but increased significantly as winter started and remained high during the winter months. During the 12 mo, mean velocity changed from 4.043 km/s (in June) to 4.961 km/s (in February) for trees and from 2.789 km/s (in June) to 3.563 km/s (in February) for logs. Average velocity of the trees measured during winter months (November to February; temperature was below freezing) was about 16% higher than that measured in other seasons (May to October; temperature was above freezing). Average velocity of the logs measured during winter months was about 23% higher than that measured in other seasons. All log samples were laid on the ground in the woods and became buried under snow during winter.

The increased acoustic velocities in trees and logs during winter primarily resulted from the

phase change of moisture state in wood cells: from water to ice. We observed that moisture content of the logs remained greater than 100% throughout the field monitoring process. This indicates that the wood cell cavities in both trees and logs were filled with free water that accounted for 76% or more of the total water. Also, about 24% of water (the FSP for red pine wood [Bodig and Jayne 1982]) was chemically bonded within the cell walls as bond water. When the temperature dropped to below the freezing point (0°C), the free water in the cell cavities froze and crystallized as ice (Kubler et al 1973). Consequently, the composition of wood in trees and logs changed from “wood substance + water” to “wood substance + water + ice.” The higher acoustic velocity in ice (ice is 3.800 km/s; water is 1.482 km/s at 20°C) is contributed to the increase in acoustic velocity measured in trees and logs when wood temperature drops below 0°C.

The other contributing factor for increased acoustic velocity in trees and logs during winter is the effect of temperature on modulus of elasticity (MOE) of wood itself. Based on a study of temperature effect on mechanical properties of standing lodgepole pine trees, Silins et al (2000)

suggested that change in the mechanical properties of both free water in the lumens and wood itself could be involved in the temperature dependence of mechanical properties of living trees. Many studies on dry wood showed that MOE of wood changed linearly with temperature across a broad range of temperatures (Gerhards 1982). When wood is cooled below normal temperature, its MOE increases, thus resulting in an increased acoustic velocity.

Relationships between Acoustic Velocity and Ambient Temperature

Figure 6 shows the direct relationships between acoustic velocity and ambient temperature for both trees and logs. Ambient temperature represents average air temperature divided by duration of each field testing. Error bars represent ± 1 SD of acoustic velocity. Similar to the laboratory results from green specimens (Gao et al 2012), the field data indicated that ambient temperature had different effects on acoustic velocity at different temperature ranges. The V - T relationships can be characterized by the fol-

lowing segmented linear regression models at three different temperature ranges:

$$V = a + bT \begin{cases} -11^{\circ}\text{C} \leq T \leq -2.5^{\circ}\text{C} \\ -2.5^{\circ}\text{C} \leq T < 0^{\circ}\text{C} \\ 0^{\circ}\text{C} < T \leq 30^{\circ}\text{C} \end{cases} \quad (1)$$

where a and b are regression coefficients. Table 1 summarizes results of regression analysis for both trees and logs.

In the range of 0-30°C, log acoustic velocity remained relatively constant with a mean value of 2.836 km/s and a coefficient of variation of less than 1%. Conversely, tree acoustic velocity generally decreased slightly when temperature increased. Regression analysis showed a good linear relationship between tree velocity and ambient temperature with an R^2 of 0.78. The regression coefficient of the mathematical model indicates a 74.4-m/s increase in tree velocity with ambient temperature decreasing 10°C. Statistical comparison analysis indicated no significant differences among tree velocity values at 0, 20, and 30°C (with a 95% level of confidence), suggesting that tree acoustic velocity could be

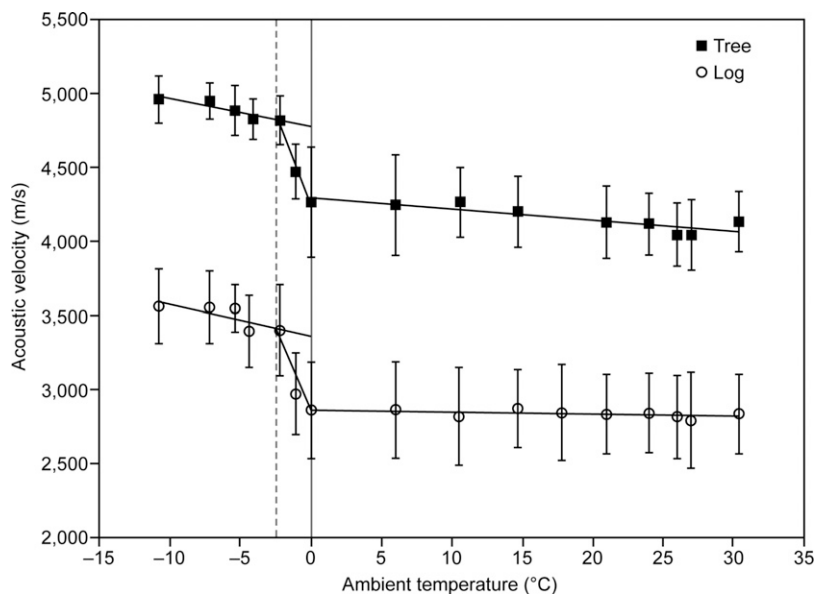


Figure 6. Effect of ambient temperature on acoustic velocity of red pine (*Pinus resinosa*) trees and logs (error bars represent ± 1 standard deviation of acoustic velocity).

Table 1. Segmented linear regression models of V - T relationships for red pine trees and logs.

Temperature range	Trees: $V_{tree} = a + bT$			Logs: $V_{log} = a + bT$		
	a	b	R^2	a	b	R^2
-11 to -2.5°C	4779.0	-18.634	0.85	3361.8	-21.534	0.63
-2.5 to 0°C	4242.0	-251.92	—	2858.0	-223.2	—
0 to 30°C	4292.6	-7.445	0.78	2862.6	-1.5169	0.37

treated as constant when ambient temperature was above 0°C and below 30°C.

Below freezing, acoustic velocity of both trees and logs increased as ambient temperature decreased. There was a dramatic shift in velocity of both trees and logs in the temperature range of -2.5 to 0°C. This phenomenon is similar to what was observed in the laboratory investigation (Gao et al 2012). As previously discussed, this velocity shift was primarily caused by phase transformation of the free water in wood cells. Because of the limited data points obtained in this temperature range, an R^2 value for the regression analysis was not appropriate. However, the velocity trend in this region undoubtedly shows a very rapid rate of change for both trees and logs. On average, acoustic velocity increased by 630 m/s for trees and 558 m/s for logs as ambient temperature decreased from 0 to -2.5°C.

When ambient temperature dropped below -2.5°C, acoustic velocity of the trees and logs continuously increased but at a much slower rate. From -2.5 to -11°C, acoustic velocity increased on average about 19 m/s for trees and 22 m/s for logs with ambient temperature decreasing each Celsius degree.

Analytical Models for Temperature Adjustment

Absolute values of acoustic velocity of trees and logs are affected by species, age, stand, and growing conditions. Therefore, the direct relationships between velocity and ambient temperature established in this study may not be suitable for making a temperature adjustment for other field testing situations. In a study modeling the effect of temperature on wood mechanical properties, Barrett et al (1989) suggested that a model based on the change in a

property relative to a base temperature would tend to minimize differences in prediction across percentile levels of the property distribution. Green and Evans (2008) examined data sets of several softwood species (Douglas-fir, southern pine, Spruce-Pine-Fir, and western hemlock) and concluded that basing a model on a change in MOE with respect to temperature, rather than modeling the absolute value of MOE vs temperature, helps to mitigate potential differences caused by species. They also reported that the effect of lumber quality on percentage of change in MOE is minimal. In considering these previous studies on modeling the effect of temperature on mechanical properties, we speculate that a similar approach could be used to develop analytical models based on the change in acoustic velocity relative to a base temperature and that these models might have applicability to species, ages, stands, and growing conditions other than those we tested in this study. We selected 20°C as the base temperature in this study. The percentage of change in velocity is defined as

$$\Delta V(\%) = \left(\frac{V_T - V_0}{V_0} \right) \times 100 \quad (2)$$

where V_T is acoustic velocity at temperature T and V_0 is acoustic velocity at 20°C.

Figure 7 shows the velocity change ΔV in relation to ambient temperature for both red pine trees and logs. Similar to the V - T relationships, a significant change in the slope of the ΔV - T relationship occurred at the freezing point and -2.5°C. The ΔV - T relationships for both trees and logs can be characterized by the following segmented linear regression models at three different temperature ranges:

$$\Delta V_T = a + bT \begin{cases} -11^\circ\text{C} \leq T \leq -2.5^\circ\text{C} \\ -2.5^\circ\text{C} \leq T < 0^\circ\text{C} \\ 0^\circ\text{C} < T < 30^\circ\text{C} \end{cases}$$

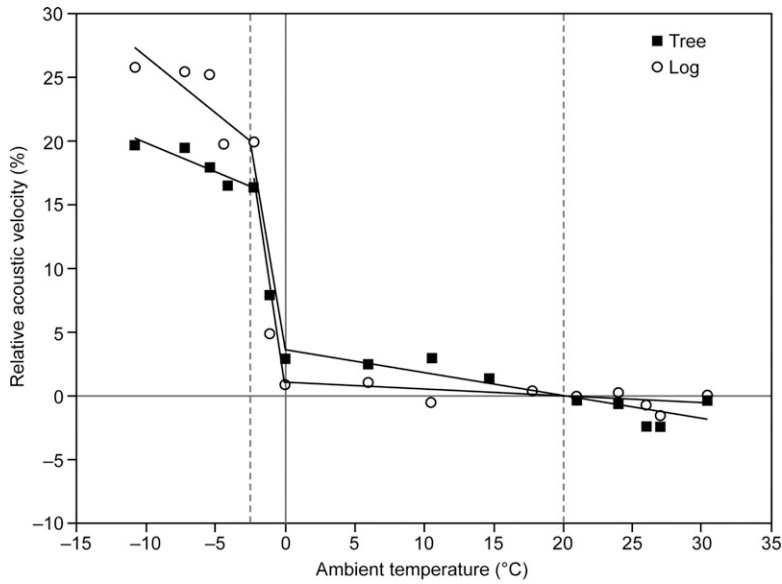


Figure 7. Effect of ambient temperature on change in acoustic velocity relative to 20°C.

Regression coefficients (a and b) and coefficients of determination (R^2) of the linear models were tabulated in Table 2. For the regression between -2.5 and 0°C , an R^2 value was not provided because of limited data points.

In the range of 0 – 30°C , the velocity change for logs relative to the reference temperature was minimal, ranging from 1.1% at 0°C to -0.5% at 30°C . The velocity change for trees had a clear inverse relationship with ambient temperature. At 0°C , Eq 3 predicts a 3.6% increase in tree velocity. At 30°C , there would be a 1.8% decrease.

In the range of 0 to -2.5°C , ΔV values of both logs and trees changed at a rapid rate. If a linear relationship is assumed with ambient temperature decreasing 1°C , ΔV increased 6.1 units for trees and 7.6 units for logs. In such a small temperature window, it would be hard to accurately predict the ΔV values because ambient tempera-

ture could change during the field testing process and the precision of temperature measurement could be affected by the temperature sensor used and wind speed at the time of measurement.

When ambient temperature was below -2.5°C , the velocity change for both trees and logs continuously increased as ambient temperature decreased. When the temperature declined from -2.5 to -11°C , ΔV increased on average about 0.45 units for trees and 0.88 units for logs for each 1°C decrease in temperature.

Table 3 tabulated ΔV values for red pine trees and logs that were derived from the analytical models. Because acoustic velocity is more sensitive to temperature changes below freezing, ΔV values are tabulated at 1°C increments from -11 to -2.5°C and at 2°C increments from 0 – 30°C . From a practical standpoint, acoustic velocities of trees and logs

Table 2. Analytical models for temperature adjustment relative to a base temperature of 20°C .

Temperature range	Trees: $\Delta V_{tree} = a + bT$			Logs: $\Delta V_{log} = a + bT$		
	a	b	R^2	a	b	R^2
-11 to -2.5°C	15.332	-0.4497	0.85	17.807	-0.8805	0.61
-2.5 to 0°C	3.61	-6.1182	—	0.909	-7.6004	—
0 to 30°C	3.61	-0.1804	0.78	1.0721	-0.0536	0.37

Table 3. Acoustic velocity change (ΔV) of red pine trees and logs in the range of -11 and 30°C .

Ambient temperature ($^{\circ}\text{C}$)	Tree ΔV (%)	Log ΔV (%)	Ambient Temp ($^{\circ}\text{C}$)	Tree ΔV (%)	Log ΔV (%)
-11	21.0	27.5	6	2.5	0.8
-10	20.6	26.6	8	2.2	0.6
-9	20.1	25.7	10	1.8	0.5
-8	19.7	24.9	12	1.4	0.4
-7	19.2	24.0	14	1.1	0.3
-6	18.8	23.1	16	0.7	0.2
-5	18.3	22.2	18	0.4	0.1
-4	17.9	21.3	20	0.0	0.0
-3	17.4	20.4	22	-0.4	-0.1
-2.5	17.2	20.0	24	-0.7	-0.2
0	3.6	1.1	26	-1.1	-0.3
2	3.2	1.0	28	-1.4	-0.4
4	2.9	0.9	30	-1.8	-0.5

measured well above freezing may not need a temperature adjustment because the velocity changes observed were not large enough to have practical significance.

CONCLUSIONS

This study investigated the effects of seasonal temperature changes on acoustic velocity of red pine trees and logs for 12 consecutive months and for temperatures between -11 and 30°C . The results of this field investigation are summarized as follows:

1. Ambient temperature had a significant effect on acoustic velocities of trees and logs in winter or when temperature was below the freezing point of water. The TOF acoustic velocity of red pine trees measured in winter was 16% higher than that measured in other seasons. Resonance-based acoustic velocity of red pine logs measured in winter was 23% higher than that measured in other seasons. The increase of acoustic velocities measured in winter was attributed to the phase change of free water in wood cells and increasing MOE of wood.
2. When ambient temperature was above freezing, log acoustic velocity remained relatively constant, whereas tree acoustic velocity decreased slightly in a general trend with increasing temperature. From a practical stand-

point, both tree and log velocity can be treated as constant when ambient temperature is above 0°C .

3. A dramatic shift in velocity of both trees and logs occurred in the temperature range of 2.5 to 0°C . On average, acoustic velocity increased by 630 m/s for red pine trees and 558 m/s for red pine logs as ambient temperature decreased from 0 to -2.5°C . When ambient temperature dropped below -2.5°C , the acoustic velocity of trees and logs continuously increased but at a much slower rate.
4. Results of this study indicate that acoustic velocities of trees and logs measured at different climates or different seasons can be adjusted to a standard temperature if measurements were conducted well above freezing or well below freezing. However, measurements conducted around freezing could cause complications in making temperature adjustments. Users should avoid conducting field testing on trees and logs when wood temperature is around the freezing point.
5. Analytical models were developed based on the percentage change in acoustic velocity relative to the acoustic velocity at a base temperature of 20°C . It was speculated that these models might have applicability to species, ages, stands, and growing conditions other than those tested in this study. Additional experimental work is needed to test this hypothesis.

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