

Temperature dependence of sound wave propagation in as a diagnostic tool for healthy and rotten black alder (*Alnus glutinosa* (L.) Gaertn.) trees trunks

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Abstract. The aim of this study was to determine how thermal conditions affect the speed of sound wave propagation, in trunks of living alder *Alnus glutinosa* (L.) Gaertn. trees. This method is practiced when diagnosing the presence of internal decay in standing trees. Field work was carried out four times at different temperatures (+13°C, +3°C, -7°C and -16°C) using an Impulse Hammer. There was a significant correlation between the thermal conditions and the speed of sound wave propagation. Therefore, temperature must be taken into account to correctly diagnose tree health and timber quality.

Key words: alder, speed of sound wave propagation, temperature, internal decay, Impulse hammer

1. Introduction

Rational forest management, next to conducting regular inventories to collect information on the quantitative state of forest resources (dimensions and number of trees, stock, assets, growth), requires that qualitative characteristics be defined which determine the health and stability of tree stands, as well as its technical quality, including the occurrence of internal decay. Assessing health status is important for single, naturally or historically significant trees (i.e. natural monuments), and also for entire stands. Among the characteristics tested in the process of assessing health status, one of the most difficult is diagnosing internal decay in the trunk and root system. Identifying the presence of internal decay can be an invasive procedure (i.e. by drilling with an increment borer or resistograph needle) or non-invasive (Nondestructive Evaluation – NDE). Tests are made using sound, ultrasound, X-rays, etc. One of the simplest, commercially available devices for non-invasive measurement is the impulse hammer,

using the measurement of the speed of sound wave propagation in wood. On the basis of the obtained results (speed in m/s), the presence of internal decay in a tree trunk is confirmed and its extent is estimated in the cross-section. The selected test device is so simple and relatively inexpensive that it may provide an opportunity for wider use not only for arboreal treatments, but also in forestry. Unfortunately, not enough information exists on the scale of propagated sound wave speeds of the trunks of different tree species, trees with varying degrees of decomposition, different environmental conditions and various outdoor conditions when the measurements are taken.

The acoustic properties of wood depend on many internal factors (hardness of the wood, wood grain, cracking, moisture content) and external ones (season, and related to this, the activity of the tree, temperature). Research shows a positive effect of temperature on the speed of sound wave propagation (Sandoz et al., 2000). Other studies on changes in the mechanical properties of wood in subzero temperatures were conducted by Silins

et al. (2000). In temperatures below 0°C, the authors observed a significant increase in two parameters: the modulus of elasticity (E), also called Young modulus, and the modulus of rupture (MOR). Frozen trunks showed an increased modulus of elasticity of 38% and an increased MOR of 52% relative to the measurements in spring. It was demonstrated that temperature has a significant impact on the mechanical properties of wood (Silins et al., 2000), and thus it may also impact the conduction properties of sound waves through wood.

Other researchers note that the discrepancies in the measurements of mechanical properties can also result from the varying water content of the wood and its physical state depending on the season. Schmidt and Pomeroy (1990) showed that when the temperature of timber dropped from 0°C to -12°C, the force required to bend a tree trunk quadrupled. The authors explained this increased stiffness of wood in subzero temperatures by the formation of ice in the residual water remaining in internal vessels. Changes in the mechanical properties of wood were also observed during the process of subjecting dried lumber to temperatures above and below freezing. Koch (1996) observed that the greatest increase in timber strength occurred at temperatures below 0°C and a relative humidity at or above the fibre saturation point. It should be noted, however, that a live tree and lumber differ in their humidity content, and so comparing them may be erroneous.

The aim of this study is to determine the relationship between ambient thermal conditions and the results of measuring the speed of sound wave propagation in the trunks of live alder trees during positive and negative temperatures, with subzero temperatures being typical for the period of increased logging activity in forests.

2. Methodology

Measurement method

The essence of measuring the speed of sound wave propagation by Impulse hammer is to assess the health condition of a tree based on the result of the speed with which the propagated sound waves move through the wood in a perpendicular direction to the heartwood. The measurement takes place between a probe generating a sound wave (after being hit with a hammer) and a receiving probe, driven into the wood at opposite sides of the trunk. Both probes (coupled with a wire to a recorder) are placed under the bark in the layers

of wood, so that the injuries to the trunk are small and also treated with the application of an antifungal agent to maintain the non-invasiveness of the method. Based on the distance between the two probes (the values are manually entered into the device on the basis of calliper measurements) and the time of wave flow, the device calculates the speed, which is the basis of diagnosing the presence or absence of internal decay in the trunk.

Expressing the result in the form of velocity (m/s) enables the interpretation and comparison of data, regardless of the thickness of the studied trees. The basis for diagnosing the occurrence of internal decay by measuring the speed of sound wave propagation is the speed of the propagation and its changes depending on the health condition of the tree trunk. Sound moves in the most rigid medium, avoiding areas of soft decay. The occurrence of internal decay in the central part of a trunk's cross-section results in a decrease of the wood's elasticity near the heartwood, which increases the distance (and simultaneously, the time) that the sound wave must travel through the wood (Sandoz et al., 2000). As a result, the device provides a result that is significantly lower than that expected for the healthy tree.

According to Wang et al. (2004), a single measurement of the speed of a propagated sound wave is able to determine the presence of internal decay, provided that it occupies at least 20% of the cross-sectional area of the trunk. The likelihood of a correct detection of decay is high when the time of sound wave propagation is longer than 10% (or more) of the expected value for a healthy tree (Wang et al., 2004). Identical results were obtained by other authors (Hailey, Morris 1987; Matheck, Bethge 1993; Yamamoto et al. 1998), indicating a similar registered level of change in the speed of sound (a decrease of approximately 10–15%) as a result of wood decay caused by parasitic fungi. In unpublished studies by Orzechowski (on spruce, alder), it was found that when about 20% of the cross-section of the tree is decayed near the heartwood, a result of even 40% lower speed is obtained in the propagation of sound waves than in healthy trees.

According to Mańkowski and Górski (2004), practical use of the method described above depends on using it on trees of an appropriate thickness (the distance between the probes should be at least 20 cm). In the case of smaller distances between the two probes, the authors obtained highly inflated readings. Furthermore, the energy creating the sound wave in a tree with a diameter smaller than 20 cm can cause the opposing probe to fall out (Budniak 2012).

Determining the speed of the propagation of sound waves required the distance between the probes to be measured. The option for hardwoods was selected in the measuring device. The audio signal was generated by performing a single blow with a hammer (integrated with the measuring device) on the top part of the probe. Measurements were made at each setting until three subsequent results similar to each other were obtained (a difference of 1–2%). After they were accepted, the device provided the average of the last three measurements, which were recorded as the final result.

To determine the temperature, a thermometer calibrated in the Celsius thermometric scale was used, and the UM numerical model forecasts for the 4 km grid (<http://meteo.pl/>) were used to control for the weather conditions in the days preceding the measurement. The effect of air temperature on the temperature of the interior of the trunk is likely to occur after a certain delay (heat exchange between the trunk and air takes time). Therefore, the measurement performed for a specific air temperature had to be preceded by 4–5 days of similar conditions to those of the measurement day. The study was performed at the same time of day – before noon – to eliminate differences caused by the upper layers of the tree being warmed by sunlight. The internal temperature of the tree trunk was not analysed, as it was deemed not needed in the employment of methods that are in principle non-invasive.

Verifying the incidence of internal decay was carried out by using an increment borer in only two trees with extreme speed measurement results.

In order to demonstrate the effect of thermal conditions on the speed of the propagation of sound waves in the trunks of live alder trees, statistical inference was used to disprove the null hypothesis that thermal conditions have no effect on the results of measuring the speed of sound wave propagation in the trunks of live alders in a radial direction. The applied statistical methods are cited in the description of research results.

The study subject

Ten black alder trees growing in a small stand (0.5 ha) in moist forest habitat were selected as the study subjects. Administratively, this area is located in the Wilanów district of the capital city of Warsaw in the Chojnów Forestry District (RDLP Warsaw). The coordinates for the study area are N 52°8'16.24" and E 21°8'14.01" (according to Geoportal.pl). Live trees of varying thickness (from about 20 to almost 50

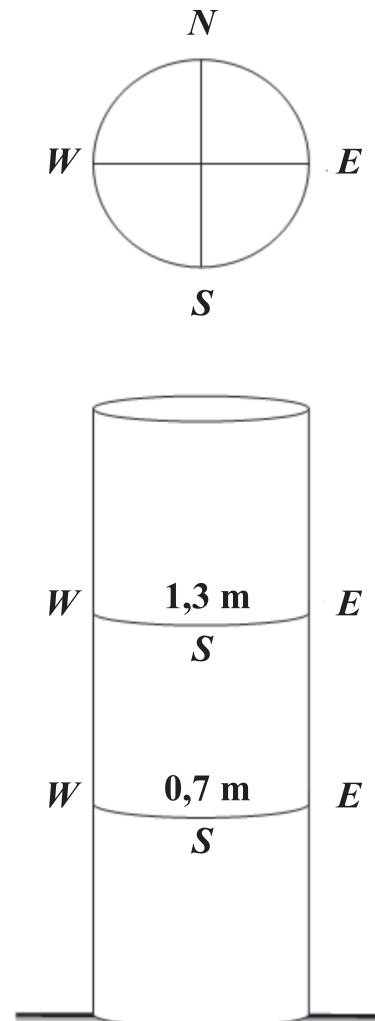


Figure 1. Diagram of the location of the measurement points on the alder trunks. The probes were located according to the geographic directions.

cm DBH) were selected, which allowed us to assume that they have internal decay within their trunks. The selected trees are not a sample of the entire stand, but only an easily found sample group to test the method. Field work was carried out on 21.10.2011, 27.01.2012, 02.02.2012 and 17.05.2012.

Each tree was given a number imprinted on its bark in order to identify it when repeating successive measurements. Each tree was marked with measurement points located to the north, south, east and west. Measurement planes were deployed at two heights:

0.7 m and 1.3 m (Fig. 1). This gave a total of four measurements on one tree and 40 for the entire study population in one repetition. A total of 160 measurements were performed. Tree no. 6 was excluded from the analysis because of large measurement errors due to its small thickness (12 cm diameter at breast height) and the fact that the opposing probe was punched out from the trunk by the generated sound wave.

3. Results

Based on descriptive statistics (Table 1), it can be seen that the results obtained at subzero temperatures differ not only from the results obtained at temperatures above zero, but they are also more diverse. When the temperature drops below 0°C, all calculated statistics show a significant increase. At a temperature of -7°C, the average speed of sound was approximately 12% higher than the speed of sound at temperatures above zero, and about 22% less than the speed of sound at a temperature of -16°C. The average speed of the propagation of sound waves measured at the lowest temperature

of -16°C proved to be as much as about 44% higher than the speed of the propagation of sound waves at temperatures above zero. The speed of sound measured at temperatures of 3°C and 13°C was very similar, and the difference was not statistically significant.

The calculated descriptive statistics lead to the conclusion that temperature conditions significantly influence the speed of sound wave propagation in the trunks of live alder trees, but to be sure of the accuracy of this regularity, the differences were tested to confirm their statistical significance.

Because successive measurements were carried out on the same trees (and in the same locations and directions on the trunk), but at different temperatures, a set of four dependent samples exists. Therefore, the one-way analysis of variance was used to calculate the results (Bruchwald 1997).

The normal distribution was tested. The level of significance adopted for the statistical analysis was 0.05. Based on probabilities test p , there was no reason to reject the assumption of a normal distribution for temperatures at 13°C, 3°C and -16°C. In the case of

Table 1. Descriptive statistics for speed of sound wave propagation through the alder wood at different temperatures

Variable	Descriptive statistics							
	N important	average	median	minimum	maximum	variance	std. dev.	var. coef.
13°C	36	1111	1129	914	1332	15220	123	11.1%
3°C	36	1103	1130	895	1344	14514	120	10.9%
-7°C	36	1238	1258	954	1460	20494	143	11.6%
-16°C	36	1589	1635	1139	1945	38801	197	12.4%

Table 2. The results of Friedman' ANOVA test

Friedman's ANOVA and Kendall's coefficient of concordance				
Chi ² , ANOVA ($N = 36$, $df 3$) = 89.96667 $p=0.00000$				
Coefficient of convergence = ,83302 r average rank = ,82825				
Variable	Rank average	Rank sum	Average	Std. dev.
13°C	1.6	59	1111	123
3°C	1.4	52	1103	120
-7°C	3.0	107	1238	143
-16°C	3.9	142	1589	197

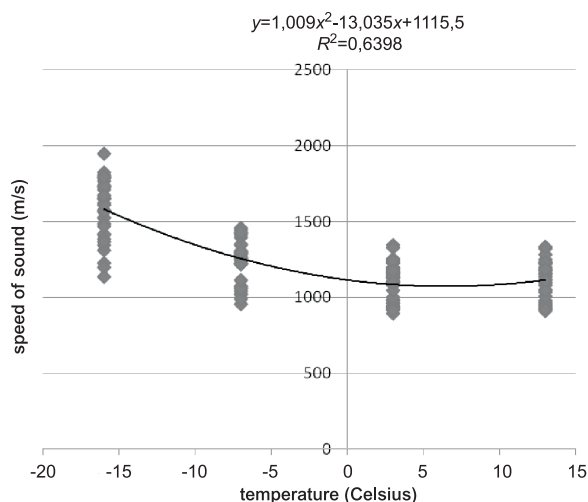


Figure 1. The relationship between the speed of sound wave propagation in the trunks of live alder trees and temperature (polynomial regression)

-7°C, the Shapiro-Wilk test showed a $p < 0.05$, so it must be assumed that the distribution of the dependent variable for the whole set of data is not normal. In view of this fact, the Friedman non-parametric statistical test was conducted using statistical software (Table 2).

The p value (all zeros mean that the p result is so small that it does not fit on the scale used in the software program) obtained by the Friedman test (Table 2) was lower than the accepted level of significance of 0.05. Thus, there are grounds for rejecting the null hypothesis stating that thermal conditions do not significantly impact the speed of sound wave propagation in live alder tree trunks, thus allowing an alternative hypothesis to be adopted.

In order to derive the equation of the function describing the dependence of the propagation of sound waves on thermal conditions (Fig. 2), data were calculated using Microsoft Excel 2007.

The coefficient of determination $R^2 = 0.6398$ (correlation coefficient of 0.8) suggests that the described relationship is strong. It should be noted that the results of the correlation probably would have been even higher if the measurements were made for a greater number of repetitions (i.e. for every 5°C of temperature difference).

When analysing the Friedman ANOVA test (Table 2) and the relationship between the speed of sound wave propagation in live alder tree trunks and temperature (Fig. 2), it can be concluded that the significance of the effect of temperature on the speed of the sound wave is

determined by the negative values of this parameter in the Celsius scale.

4. Discussion

This study did not verify the health condition of the sample trees, but only tested the differences in the measurements resulting from the use of the Impulse hammer during various seasons and at different ambient temperatures. Therefore, it was decided not to fell or drill all of the tree to determine the occurrence of decay. Four test holes were drilled (two in two trees – one was diagnosed as healthy, and the other as diseased) only to check that the device was functioning properly, whose effectiveness was confirmed by previous work (Orłowski 2010; Cybulski 2012; Grabowski, 2012) carried out in the Department of Forest Management Planning, Geomatics and Forest Economics of the Warsaw University of Life Sciences – SGGW, under the direction of Ph. D. Orzechowski.

The obtained study results showed that temperature significantly affects the result of the speed of sound wave propagation in live alder tree trunks. Many researchers indicate negative temperatures as the cause of changes in the mechanical properties of wood (and this then influences the acoustic properties). The freezing of water in wood during winter will cause it to stiffen and increase its elasticity. It is therefore useful to analyse the equation for the velocity of a sound wave:

$$C^2 = E/\rho \text{ (m/s)}$$

where:

C – speed in m/s

E – modulus of elasticity in $\text{kg/s}^2\text{m}$

ρ – density in kg/m^3

Therefore:

$$(d/t)^2 = E/\rho \text{ (m/s)}$$

where:

d – thickness of the trunk in m

t – transit time of a wave in s

In analysing the above relationships, we can conclude that the transit time of the wave (the trunk thickness is constant for all four repetitions of the measurements conducted at different temperatures) depends on the modulus of elasticity and density. A study by Silins et al. (2000) demonstrated that at subzero temperatures, the modulus of elasticity is higher as the temperature decreases. On the other hand, the freezing of water and the formation of ice inside the trunk is manifested by a decrease in the density of the water itself, even though this cannot be said for the trunk containing

Table 3. The results for the tree No. 1 and 10

Tree number	Measurement number	DBH between probes [cm]	Speed of sound waves [m/s], at temperature	
			3°C	-16°C
1	W107N	47 cm	1344	1797
	W107W	40 cm	1328	1730
	W113N	38 cm	1158	1525
	W113W	33 cm	1186	1622
10	W1007N	42 cm	927	1735
	W1007W	42 cm	918	1796
	W1013N	37 cm	1103	1608
	W1013W	36 cm	1178	1670

the water. Wood tissue reacts to a drop in temperature by contracting, thereby increasing the density of the trunk. In effect (comparing these observations with the equation), the transit time of a sound wave through wood in subzero temperatures is reduced, and the speed of sound wave propagation increases.

The equation illustrating the dependence of sound wave speed on temperature can be used in practice, provided that a correction is made to ultimately determine the separation point in the measured values between trees without decay and trees with decay under given temperature conditions. However, situations occur where the measurement of the tested characteristic is misleading. As the measurement results show for tree no. 10 (with obvious decay) and no. 1 (healthy), at a temperature of -16°C, the difference in the speed of sound wave propagation between the thick trunks of healthy and diseased trees can be unclear (Table 3).

Diagnosing a tree as diseased based on measurements taken in positive temperatures (sound velocity of <1000 m/s in both directions at a height of 0.7 m indicates an undeniable presence of decay) is different from a diagnosis at -16°C because under these conditions, the speed of sound wave propagation is one that is typical for a healthy tree. This is due to the creation of ice bridges formed from the freezing water in tree trunks with extensive decay. As a result of such bridges, the acoustic conductivity of trees with decay may be the same as the conductivity of healthy trees. Of course, the direction of the bridge must be the same as the direction of the measurement. This problem, however, requires

further study by determining an appropriate sample in favourable conditions of low, subzero temperatures.

5. Conclusions

1. Thermal conditions significantly influence the speed of sound wave propagation in the trunks of live alder trees. The value of the air temperature (especially negative) should therefore be taken into account before diagnosing internal decay using the method described above.

2. A change in temperature conditions ranging from 3°C to 13°C does not significantly influence the results obtained. Taking measurements at low, subzero temperatures (-16°C) is not recommended due to:

- the possibility of making an incorrect assessment of trees with internal decay due to the development of ice bridges in the rotted portions of the trunk

- the inability to make an effective correction to the elaborated function (describing the dependence of sound velocity on temperature), with respect to the claim made above

- the difficulty of operating the device.

3. Negative temperatures (-7°C to 0°C) provide the conditions enabling a diagnosis to be made of the presence of internal decay. The speed of sound wave propagation in potentially decayed tree trunks was lower than in healthy tree trunks when measured during both positive and negative temperatures.

4. Diagnosing internal decay by using an Impulse hammer is not suitable for thin trees (under 20 cm thick) because of the risk of a large measurement error.

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