Ultrasonic evaluation of mechanical properties of wood in standing trees

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ABSTRACT

Methods based on propagation of stress waves phenomena indicate particular usefulness in diagnosis and assortmentation of raw material. It has been demonstrated that ultrasonic measurements made both on sawn timber and on standing trees produce satisfactory results in predicting certain mechanical properties of sawn timber obtained from the analysed raw material. The highest correlation has been observed between the velocity of ultrasounds along trunks and the modulus of elasticity of sawn timber obtained from them. A similar correlation with the bending strength has also been satisfactory. To ensure the correct interpretation of the results, it is recommended that studies should be conducted to detect and locate inner rot in standing tree trunks. The studies can be performed by taking measurements of ultrasonic wave propagation transversely in trunks in a potentially defected area and an area free from defects.

INTRODUCTION

Development of non-destructive testing made it possible to use the technique for the purposes of diagnosis and assortmentation of raw material and in a forest taxation work. Acoustic methods based on the phenomena accompanying propagation of longitudinal stress waves and transverse vibration demonstrate their particular usefulness for such testing. Based on measurements of round sawn timber [Dzbeński 1981], it was found that the velocity of transverse ultrasonic waves propagation in pine trunks could be a good indicator of mechanical properties of sawn timber obtained from them, e.g. aircraft timber. Similar results based on acoustic methods were achieved among others by Jayne /1959/, Marra, Pellerin and Galligan /1966/, Kaiserlik and Pellerin /1977/, Aratake and Arima /1994/, Sandoz /1996/, Ross, McDonald, Green and Schad /1997/, Wang and others /2000/.
The results of the above-mentioned tests suggested a possibility of detecting hidden defects in round wood, e.g. inner rot in telecommunications poles and masts [Breeze, Nilberg 1971], and in standing tree trunks [Sandoz, Lorin 1994, Sandoz 1999]. Using acoustic methods, Ross, De Grott, Nelson /1994/ were detecting biological degradation of wood in tree trunks, while Dzbeński and Wiktorski /2004, 2007/ - in pine and spruce trees in Polish forests.

MATERIALS AND METHODS

Mechanical properties of sawn timber in the light of defectoscopic testing of sawn timber raw material.

Ultrasonic methods, used already thirty years ago e.g. at the Faculty of Wood Technology, Warsaw University of Life Science demonstrate particular usefulness for assortmentation of saw logs. They successfully replace the testing conducted up to now with the use of traditional (destructive) methods on trees specimens. Traditional methods required a long time to perform tests and provide only an approximate evaluation of a large batch of material on the basis of testing of a small sample population. 100% measurements were conducted on pine logs using ultrasonic waves propagated transversely in the trunk (by equipment of 541 type produced by UNIPAN, Warsaw). The bark was cut through with conic or needle concentrators extending gauge probes (heads).
It was found that the velocity of ultrasound propagation can be an important (r=0.588 … 0.647) indicator of mechanical properties determined longitudinally in sawn timber obtained from the round raw material where waves with the velocity of $c_{\perp}$ travel in sapwood with a high moisture content over a heartwood area with knots (or inner rot) grouped in a core wastewood zone. The testing results are presented in table 1.

Table 1. Relationship between velocity of ultrasounds conducted transversely in trunks and selected mechanical properties of (air dried) pine sawn timber obtained from them.

Type of sawn timber properties	Regression equation $f(c_\perp)$	Correlation coefficient (r)
Bending modulus of elasticity E_g [MPa*10^2]	$E_g = 0.039\ c_\perp + 44.3$	0.647
Static bending strength R_g [MPa*10^{-1}]	$R_g = 0.230\ c_\perp + 551.1$	0.599
Longitudinal compressive strength R_c [MPa*10^{-1}]	$R_c = 0.113\ c_\perp + 290.9$	0.588

Mechanical properties of bending wood from standing tree trunks tested with the ultrasonic method.

The ultrasonic technique made it possible to test several dozen spruce trees (Picea abies Karst.) and pine trees (Pinus sylvestris L.) growing in Puszcza Augustowska (Augustowska Primeval Forest), Puszcza Romnicka (Romnicka Primeval Forest) and in Experimental Forests of the Warsaw University of Life Science in Rogów. Thus, a quick, repeatable and quasi-non-destructive (a need to make small drills to install gauge probes on the trunks) method was used. Gauge probes were made by connecting piezo-electric and electro-dynamical transducers [Dzbeński, Wiktorski 2004, 2007]. The method has shown promise for becoming commonly used in wood science metrology.

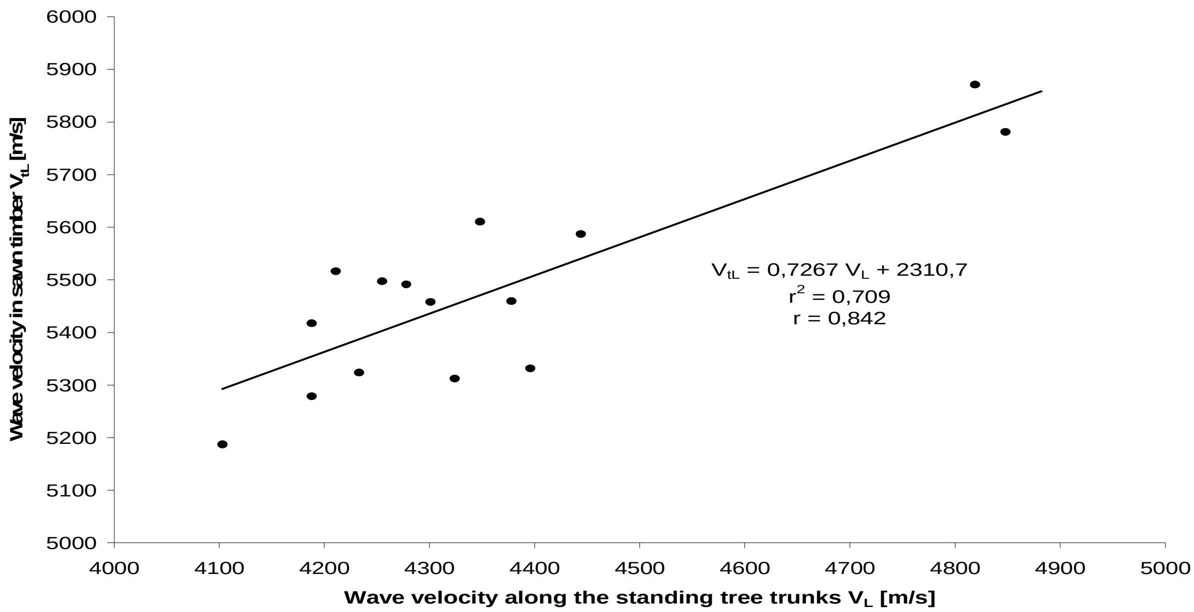

Figure 1. Correlation of ultrasonic wave velocity in standing tree trunks and sawn timber.

This paper presents results of a preliminary testing with the use of equipment of the Sylvatest Duo type from Concept Bois Technologie – Concept Bois Structure, as in Sandoz's studies, measuring selected trunks of pine trees longitudinally and transversely. After cutting the trees, their butt ends (up to 1.5 m long) were used to obtain little beams (specimens 1.2 meter long and 50 x 50 mm cross-section according to the PN-77/D-04227 standard, along radii corresponding to four geographical directions, separately from the near-circumferential and pith areas). Modulus of elasticity and static bending strength were tested according to the PN-EN 408 standard. The results of sapwood testing were correlated with ultrasonic velocity along the trunk V_L (0.8 m long section), while of sapwood and heartwood together – with the transverse ultrasonic velocity $V_\perp$ in the trunk with a diameter up to 50 cm. Above this allowable trunk diameter, the energy of the transmitted signal, measured by a millivoltmeter, reaches a critically low level, and the receiving probe registers only random disturbances. The measurement results are presented in tables 2 and 3.

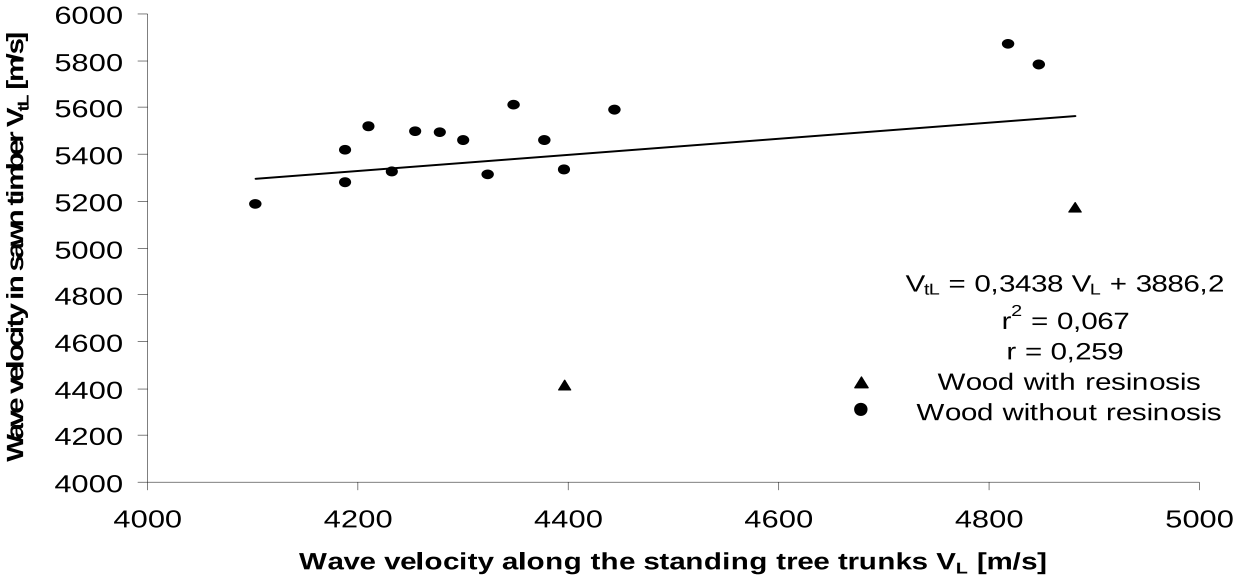

Figure 2. Correlation of ultrasonic wave velocity in standing tree trunks and sawn timber – including wood with resinosis.

Table 2. Relationship between velocity of ultrasounds conducted longitudinally in trunks and selected mechanical properties of (air-dried) pine sawn timber obtained from them, from the near-circumferential zone.

Type of sawn timber properties	Regression equation $f(V_L)$	Correlation coefficient (r)
Bending modulus of elasticity E_g [MPa]	$E_g = 5.996\ V_L + 14214$	0.867
Static bending strength R_g [MPa]	$R_g = 0.029\ V_L + 63.716$	0.663

Table 3. Relationship between velocity of ultrasounds conducted transversely trunks and selected mechanical properties of (air-dried) pine sawn timber obtained from them, from the near-circumferential zone.

Type of sawn timber properties	Regression equation $f(V_\perp)$	Correlation coefficient (r)
Bending modulus of elasticity E_g [MPa]	$E_g = 12.829\ V_\perp - 6460.9$	0.711
Static bending strength R_g [MPa]	$R_g = 0.0501\ V_\perp - 6.9027$	0.796

The studies demonstrated that the presence of wood with resinosis has a significant impact on the character of the regression equation. In the testing described above, the correlation coefficient of ultrasonic velocity propagated along the trunk and air dried sawn timber obtained from them was only 0.259 in case of population with specimens of wood with resinosis (fig. 2) and 0.842 in case of population with specimens of wood with no resinosis (fig. 1). A parallel correlation with modulus of elasticity (r = 0.867, fig. 3) and bending strength (r=0.663, fig. 4) looks similarly. Negative impact of excessive presence of resin (the so-called resinosis) caused by a fungal infection suggests that an attempt should be made to detect and locate rot in trunks of the tested trees. In case of transverse ultrasonic measurements in the trunks, the confidence level of the presented correlation coefficients is less than 0.90 due to the smaller sample group (5 trunks).

Detection of rot inside trunks of coniferous trees by means of the ultrasonic technique.

Longitudinal and transverse measurements of pine and spruce tree trunks were made using equipment of the Sylvatest Duo type, having modified the method described by Sandoz [Sandoz, Lorin 1994, Sandoz 1999]. Both the transverse heterogeneity of wood with rot (the „*Z*" coefficient of the trunk degradation) and anisotropy of elasticity properties (coefficient „*A*" of anisotropy of ultrasonic velocity - longitudinally and transversely in the trunk) were taken into account.

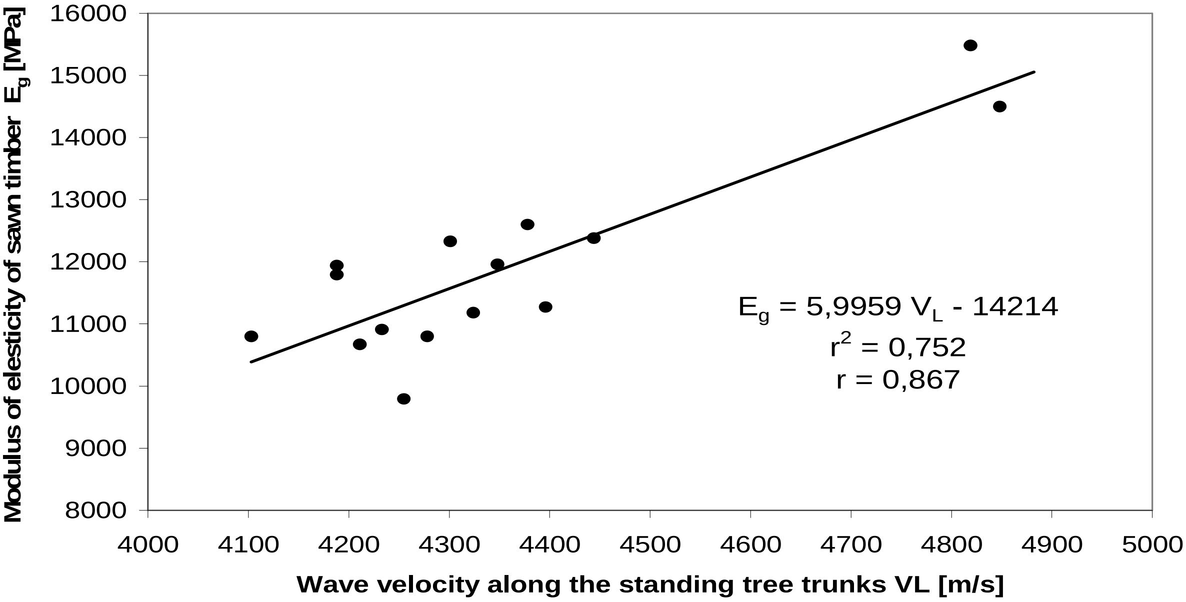

Figure 3. Correlation of modulus of elasticity of sawn timber and ultrasonic velocity along standing tree trunks.

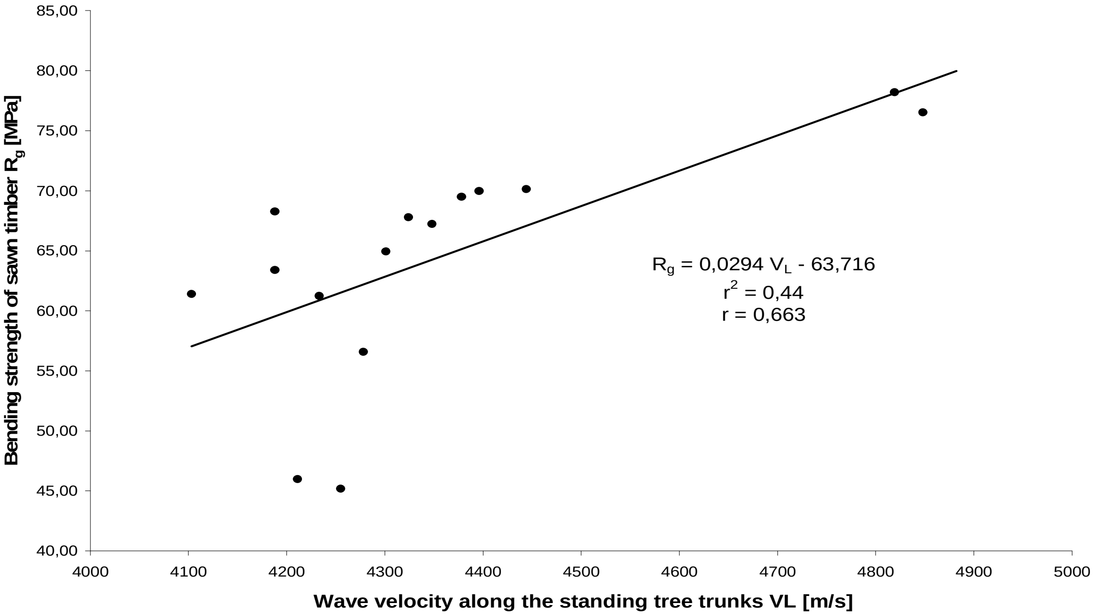

Figure 4. Correlation of bending strength of sawn timber and ultrasonic velocity along standing tree trunks.

Using the phenomenon of usually non-symmetric distribution of defects (rot, hollows, knot groups, etc.) in a cross section it is possible to describe structural transverse heterogeneity, determining the socalled „*Z*" coefficient of the trunk degradation, in the following way:

$$Z = (V_{\perp ref} - V_{\perp})/V_{\perp ref} * 100\ \% \qquad (1)$$

Where: $V_{\perp}$ - transverse wave transmission time in the trunk above the root collar;

$V_{\perp ref}$ – reference velocity (in wood with no defects, usually at the altitude of 2.0 meters above the ground).

The coefficient of transverse heterogeneity of material should be determined from the following equation:

$$K = \frac{\Delta V_{\perp}}{V_{\perp ref}} = \frac{V_{\perp 1} - V_{\perp 2}}{V_{\perp ref}} \times 100\% \qquad (2)$$

Where: $V_{\perp 1}$ and $V_{\perp 2}$ - registered wave transmission velocities in two perpendicular directions, across trunks.

The bigger the difference between the above-mentioned velocities, the higher the transverse heterogeneity of the material. The lower the measured velocities, the bigger the inner defect will be. The bigger the values of the „*K*" coefficient from the equation (2), the more the rot tends to move in relation to the pith. Examples of the measurement results are presented in table 4.

The percentage of $U_{\perp}'$ [%] of the rot area (or another inner defect) of the D diameter in a cross-section of the trunk depends on the propagation time (τ) and transverse wave velocity ($V_{\perp}$) in the trunk with an average diameter of (d), decreased to the value of ($V_{\perp}' = d/\tau'$) as a result of longer time it takes for the signal to pass through the inner rot area (τ'), i.e.:

$$\frac{\Delta\tau}{\tau} = \frac{\Delta V_{\perp}}{V_{\perp}} = \frac{D}{d} \approx U_{\perp}' \qquad (3)$$

The percentage of the rot area $U_{\perp}'$ can be also estimated by means of anisotropy of the centre elasticity method (np. wood with density of ρ and modulus of elasticity of E_{VL}) based on the following proportion:

$$A = \frac{V_L}{V_{\perp}} \leq \frac{V_L}{V_{\perp}'} \qquad (4)$$

Where: $V_L = \sqrt{\frac{1{,}35 \times E_{V_L}}{\rho}} [m/s]$ having taken account of the Poisson number [Dzbeński 1984]

Table 4. Quality characteristic of tested spruce and pine trunks (selected examples).

Percentage of rot area U'⊥ [%]	Reference velocity		Transverse velocity of fibres		Degradation coefficients			Transverse heterogeneity coefficient
	$V_{1\perp ref}$ [m/s]	$V_{2\perp ref}$ [m/s]	$V_{\perp 1}$ [m/s]	$V_{\perp 2}$ [m/s]	Z_1 [%]	Z_2 [%]	$\Delta V_{\perp}$	$K = \Delta V_{\perp} / V_{\perp ref}$ [%]
0	1269 a)	1239 b)	1329	1353	0	0	24	1.9
0	1548 a)	1408 b)	1559	1548	0	0	11	0.7
3	1440 a)	1436 b)	1510	1466	0	0	44	3.0
6,5	1305	1250 b)	1293	1318	1,0	0	25	2.0
17	1305	1250	1235	1070	5.4	14.4	165	12.6
31	1377	1354	1054	1075	23.5	20.6	21	1.5
35	1171	1065	978	1089	16.5	- c)	111	9.5
42	1341	1579	837	1012	37.6	35.9	175	13.1
44	1463	1420	1049	1086	28.3	23.5	37	2.5
61	1538	1517	1322	1276	14.0	15.9	46	3.0

a) $V_{1\perp ref} = V_{\perp 1}$ accepted after verification; b) $V_{2\perp ref} = V_{\perp 2}$ accepted after verification; c) Result rejected after verification

CONCLUSIONS

1) Velocity of ultrasonic wave propagation in coniferous standing tree trunks (pine, spruce) is a good indicator of mechanical properties of sawn timber obtained from them. Satisfactory correlations were achieved between longitudinal wave velocity (r=0.867) and transverse wave velocity (r=0.711) in standing trees trunks, and modulus of elasticity of sawn timber obtained; parallel correlation coefficients relating to bending strength (r=0.663; r=0.796), and compressive strength (r = 0.588 > 0.5139).
2) An important correlation (r=0.842) between longitudinal ultrasonic velocity in standing tree trunks and sawn timber obtained from them provides the basis for the above-mentioned correlations.
3) Strong resinosis of wood caused by a fungal infection results in a significant discrepancy of the relationships indicated in conclusions (1) and (2) and makes it necessary to conduct studies relating to presence and location of inner rot in coniferous tree trunks.

4) Irregularity of a shape or non-centric distribution of inner rot can be determined by a cross-wise measurement of heterogeneity in transverse ultrasonic conduction in the trunk („Z_1" and „Z_2" degradation coefficients); the higher their value, the more the rot tends to move in relation to the pith.
5) Low transverse ultrasonic velocity in fibres is a direct proof of the inner rot presence. The size of the rot can be determined on the basis of the „*K*" transverse heterogeneity coefficient in transverse ultrasonic conduction in the trunk, i.e. by comparing the wave velocity outside the rot area (e.g. at the altitude of 2.0 meters) to the wave velocity in a defected area of the butt end. The rot dimensions can also be described by means of the „*A*" anisotropy coefficient in longitudinal and transverse ultrasonic conduction in the trunk.

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