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ULRASONIC WAVE PROPAGATION AND YOUNG´S MODULUS OF ELASTICITY ALONG THE GRAIN OF SCOTS PINE WOOD (*PINUS SYLVESTRIS* L.) VARYING WITH DISTANCE FROM THE PITH

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ABSTRACT

Wood density, ultrasonic wave velocity and Young's modulus along the grain of Scots pine wood (*Pinus sylvestris* L.) were determined in five zones of a tree trunk cross-section differing in their distance from the pith. The microfibril angle (MFA) in the tangential walls of tracheids and the Young's modulus of cell walls were estimated. The microfibril angle was found to be the main determinant of the ultrasonic wave velocity and Young's modulus of wood along the grain.

KEYWORDS: Dynamic Young's modulus, density, cell wall, microfibril angle.

INTRODUCTION

Propagation velocity of ultrasound waves in materials, including wood, is an important parameter enabling to determine their quality characters in a non-destructive manner. It depends on the Young's modulus and density of the examined material. Therefore, for determining technical parameters of a material and their changes, it is enough to measure the ultrasonic wave propagation velocity. In material engineering, the best method for determination of the modulus of elasticity is measurement of sound velocity. Determination of Young's modulus on the basis of measurements of the compression force and the strain of the compressed sample (compression test widely applied to assess mechanical properties of materials) is not suitable in the case when the modulus is high – because the strain may be too small to measure accurately and in the case when additional phenomena contribute to the strain, e.g. creeping or deformation of sample near-surface layers – because an incorrect value of the elasticity modulus can be obtained (Ashby and Jones 1995).

Wood density is a parameter, associated with the structure of this material. Its impact on ultrasonic wave propagation has not been recognized satisfactorily yet, and some findings in this regard are contradictory. The results of numerous publications indicate that together with the increase of wood density within individual species, the ultrasonic wave velocity also increases (Sandoz and Lorin 1994, Yamamoto et al. 1998, Moliński and Marcinkowska 2007), although the correlations between these values are not always linear. On the other hand, results from other researchers, among others, Burmester (1965), Dzbeński (1984) and Marcinkowska (2005) indicate absence of relationships between the velocity of sound propagation in wood along the grain and the wood density. The above-mentioned researchers suggest that wood elastic properties and, in this way, the velocity of ultrasonic wave propagation, are most influenced by traits of its microscopic and sub-microscopic structure (Huang et al. 2003). One of the most important aspects of cell wall structure is the angle the microfibrils form with longitudinal cell axis. This angle, in the S2 layer of the secondary cell wall, is one of the main factors affecting the rigidity and strength of wood in the longitudinal direction (Cave and Walker 1994, Reiterer et al. 1999, Yamashita et al. 2000, Yang and Evans 2003). Particularly important is the angle of microfibrils in tangential tracheid walls in which it assumes smaller values than in radial walls (Sarén and Serimaa 2006, Xu et al. 2004). In conditions of continuous strain, walls with smaller microfibril inclination angle are – due to their greater rigidity; more strained and are destroyed first when loads increase. Therefore, they are responsible for tracheid mechanical properties.

Young's modulus is a measure of material stiffness, and it has a strong correlation with the material strength. In addition, the density, mechanical properties as well as microscopic and submicroscopic wood structure (microfibril angle) change in relation to their position on the trunk cross-section. The objectives of this study were: to investigate the effects of the position of samples along the radius on velocity of longitudinal ultrasonic waves propagated through wood specimens and on Young's modulus, and to investigate correlations between the propagation velocity of ultrasonic waves and pine wood density as well as microfibril angle in tangential tracheid walls (Hirakawa and Fujisawa 1995, Huang et al. 2003).

MATERIAL AND METHODS

The experiments were conducted on specimens prepared a 60-year old pine tree (*Pinus sylvestris* L) dominating in the stand. First, a log about 60 cm long was sawn at approx. 2 m above the ground. From the log was a board in N-S direction and crossing the pith. From this board were obtained specimens with the following dimensions: 20 (T) × 20 (R) × 30 (L) mm. Earlier, a batten approximately 30 mm thick was cut off the board, and it was used to determine the width of annual rings and the proportion of them of latewood, as well as to measure the microfibril angle in tangential tracheid walls. The samples were conditioned in the laboratory at T = 20–22°C and RH = 35–41 %, until the equilibrium moisture content. Density of all samples was determined using the stereometric method, and moisture content was determined in three samples from each block by gravimetric method. Linear dimensions were measured with a 0.01 mm accuracy and mass with 0.001 g accuracy. The samples were dried to oven-dry state at the temperature of 103 ± 2°C.

There was measured the passage time of longitudinal ultrasonic waves through wood along the grain. We used a "Unipan 543" ultrasonic tester equipped with measuring heads acting at 0.5 MHz frequency (input 05T20, output 05R20) – adjusted for wood examination. To ensure appropriate contact of the heads with the tested material as well as stability and repeatability of experiments, the contact surface was coated with silicon fat. The measurements were carried out with 0.02 μs accuracy. The testing pressure of about 0.15 MPa was developed mechanically (screw mechanism). Wood moisture content at the moment of investigations ranged from 7.6 to 8.2 %.

Ultrasonic wave velocity was calculated according to the following formula:

$$C_L = \frac{L_L}{t} \tag{1}$$

where: L_L – the distance passed by the wave – equal to the sample length (m),
t – time needed for the ultrasonic wave to pass through the examined sample (s).

Values of the wood dynamic modulus of elasticity along the grain were calculated using the basic physical relationship between sound velocity, density and the modulus of material elasticity:

$$C_L = \sqrt{(DMOE_L / \rho) \cdot 10^9} \tag{2}$$

where: C_L – propagation velocity of ultrasonic waves along the grain ($m.s^{-1}$),
$DMOE_L$ – dynamic modulus of elasticity along the grain (GPa),
ρ – wood density ($kg.m^{-3}$)
10^9– coefficient connected with conversion.

The above formula is acceptable for isotropic materials. In the case of anisotropic materials, it is necessary to introduce a correction (p) taking into account reduced Poisson's coefficient (Dzbeński 1984, Mańkowski and Gierlik 2001). Values of the coefficient were calculated for pine wood with using numerical values of material constants according to Aszkenazi (1978). Taking into account the value of the calculated correction (p = 0.83), wood dynamic elasticity modulus was obtained from the following formula:

$$DMOE_L = C_L^2 \cdot \rho \cdot 0.83 \cdot 10^{-9} \tag{3}$$

and the dynamic modulus of elasticity of cell walls ($DMOE_L$ c.w.) was calculated from the following relation:

$$DMOE_{L-cw} = DMOE_L \cdot \frac{1500}{\rho} \tag{4}$$

where: 1500 – density of wood substance ($kg.m^{-3}$).

Measurements of the MFA in individual tracheids were taken with the direct method as described by Fabisiak and Moliński (2007), and its mean value in the examined samples was calculated in the way described by Krauss et al. (2009).

RESULTS

Fig. 1 shows radial density variations of the examined pine wood. As the wood tissue matures, wood density increases up to about the 20th annual ring (juvenile wood zone), and then it decreases. Such character of pinewood density variability is in accordance with the literature data (Krzysik 1974, Požgaj et al. 1997, Kärenlampi and Riekkinen 2004). The mean density of the analysed annual ring zones assumes values in the interval from 438 to 497 kg.m^{-3}. Density variations within a single ring zone are negligible, as the coefficient of variation (CV) assumes values from about 1 % for the zone comprising rings from 2 to 7 counting from the pith to 8 %, for the zone of rings 17–23.

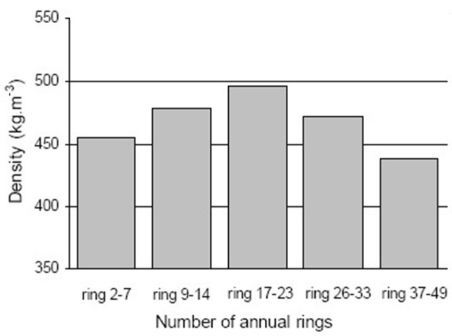

Fig. 1: Mean wood density of analysed annual ring zones.

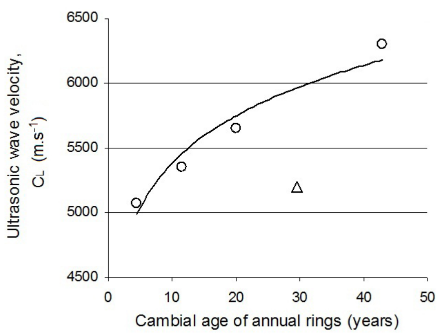

Fig. 2: Ultrasonic wave velocity vs. cambial age of annual rings. The trend line is regression line $y = 4326x^{0.0947}$.

The analysis of changes in the ultrasonic wave velocity in the cambium age function (Fig. 2) shows that the value of its propagation along the grain in solid wood tissue increases together with the increasing distance from the pith (individual points on the diagram show mean velocity values of longitudinal ultrasonic waves propagated through wood specimens for the ring zones shown in Fig. 1).

It is lower than in the neighbouring zones of the trunk cross section only in the zone comprising rings 26–33. The most likely cause of this exception from the general trend of changes of the analysed quantity is the occurrence of compression wood as indicated by the increased width of the latewood zone in annual increments. The mean proportion of latewood in four out of eight increments of this zone amounts 41 %.

Ultrasonic wave velocity variations within individual annual ring zones are small, as evidenced by values of statistical quantities of this parameter (Tab. 1), e.g. coefficient of variability (CV) which assumes values from 2.1 to 4.6 %. On the other hand, variations in the ultrasonic wave transmission velocity between individual trunk cross section zones are distinct. In the near-circumferential zone (rings 37–49), in comparison with the near-pith zone (rings 2–7), the mean ultrasonic wave velocity is by 1225 m.s^{-1}, i.e. by approximately 25 %, greater. Values of this quantity are contained in the interval of 5075–6300 m.s^{-1}, and they are similar to the data found in literature for pine wood (Raczkowski et al. 2004, Marcinkowska 2005).

The comparison of the radial variation of the ultrasonic wave propagation velocity (Fig. 2) and density of the examined wood (Fig. 1) indicates absence of unequivocal correlation between these quantities. This has also been confirmed by collating data about mean values of these quantities for the examined trunk cross section zones (Fig. 3).

Tab. 1: Mean values of ultrasonic wave velocity and statistical variables.

Cross-section zone (annual rings)	n (pcs)	$\dot{x}$	±SD	±SE	CV
		(m.s^{-1})			(%)
2–7	14	5075	192.9	51.5	3.80
9–14	14	5354	145.5	38.9	2.72
17–23	14	5650	164.5	44.0	2.91
26–33	15	5203	241.0	62.2	4.63
37–49	15	6300	134.8	34.8	2.14

where: n – number of examined samples,
$\dot{x}$ – mean,
±SD – standard deviation,
±SE – standard error,
CV – coefficient of variation

Ultrasonic wave propagation velocity in wood differing with regard to its density can be practically identical (near-pith rings 2–7 and mature wood rings 26–33) or it can differ very significantly (near-pith rings 2–7 and near-circumferential rings 37–49), although – in the latter case – wood of lower density is characterised by higher ultrasonic wave propagation velocity. Absence of a functional relation on trunk cross section between the ultrasonic wave propagation velocity and wood density is confirmed by a very low value of the determination coefficient for this relationship (R^2 = 0.146). These observations indicate that it is rather the ultrastructure of tracheid cell walls than wood density that is responsible for differences in ultrasonic wave density or their absence. These observations are also in accordance with the research results of Burmester (1965) and Dzbeński (1984) who also reported unequivocal impact of wood density on sound transmission velocity along the grain of pine wood.

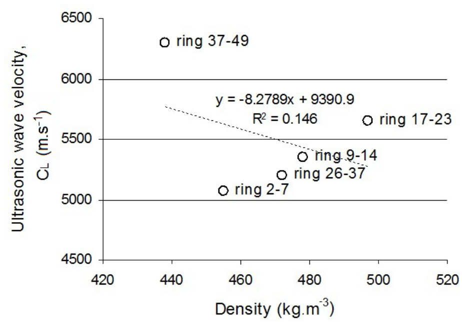

Fig. 3: Ultrasonic wave velocity vs. mean wood density of analysed annual ring zones.

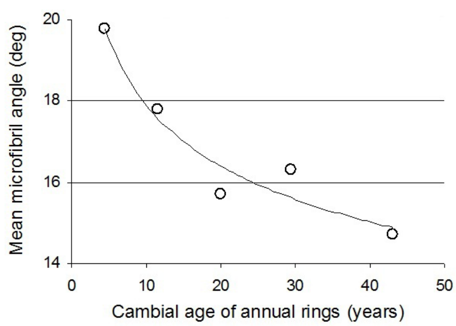

Fig. 4: Variation in the mean microfibril angle of Scots pine wood vs. the cambial age of annual rings. The trend line is regression line $y = 23.94x^{-0.126}$.

On the other hand, the analysis of data regarding wood density and ultrasonic wave transmission velocity restricted only to juvenile wood (ring zone 2–7, 9–17 and 17–23) indicates a positive correlation between these quantities. However, due to the fact that together with the wood tissue maturation (especially during juvenile tree growth) dynamic changes in its morphological traits and cell wall ultrastructure occur – tracheid length increases considerably (Fabisiak 2005) and microfibril angle declines dynamically (Lichtenegger et al. 1999) – and with increasing length of wood anatomical elements, transmission velocity of ultrasonic waves along the grain also increases (Marcinkowska 2005). It can be presumed that also in juvenile wood, transmission velocity of ultrasonic waves is determined by the cell wall ultrastructure.

Physical, mechanical and rheological properties of wood determined along the grain are strongly influenced by MFA in the S2 layer of the secondary cell wall (Reiterer et al. 1999, Kojima and Yamamoto 2004). The comparison of changes in this angle (Fig. 4) and ultrasonic wave velocity (Fig. 2) in the cambial age function of annual rings shows that values of these parameters change in an antagonistic manner, i.e. a decrease in the MFA corresponds to increased ultrasonic wave velocity.

This observation indicates the existence of a functional relationship between these parameters as shown in Fig. 5. The relationship between the ultrasonic wave velocity and MFA is negative; as the MFA increases, the ultrasonic wave velocity in wood along the grain decreases and, within the analysed interval of the MFA variability, it can be approximated by a linear function ($R^2 = 0.71$).

The data about mean values of wood density and modulus of elasticity derived from different zones of the trunk cross section are summarised in Fig. 6. The analysis of these data fails to corroborate a widely shared view about a positive relationship between wood mechanical properties and its density. This can probably be attributed to a narrow variability interval of wood density as well as to a relatively low density of the near-circumferential wood which, simultaneously, was characterised by a high modulus of elasticity. Therefore, causes of the radial variability of the modulus of elasticity should be sought in the cell wall ultrastructure.

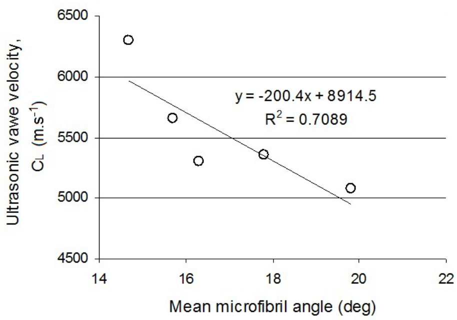

Fig. 5: Ultrasonic wave velocity vs. mean microfibril angle.

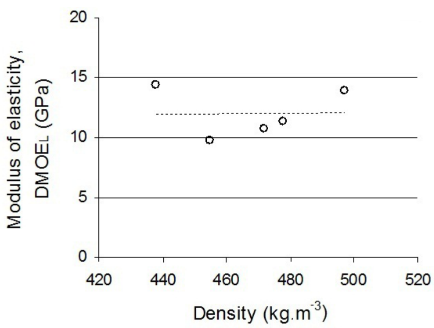

Fig. 6: The modulus of elasticity vs. density.

The analyses of the variability of the values of modulus of elasticity of wood and cell walls determined on the basis of measurements of the propagation velocity of the longitudinal ultrasonic wave as well as data about the material constants of Scots pine wood indicate that they increase together with wood tissue maturation (Fig. 7). Wood modulus of elasticity between the near-pith (rings 2–7) and near-circumference (rings 37–49) zones increases from 9.7 GPa to

14.4 GPa, i.e. by 48 %, whereas cell wall modulus of elasticity increases from 32 GPa to 49 GPa, i.e. by 53 %. The fact that cell wall modulus of elasticity is not a constant parameter indicates that its value does not depend exclusively on wood density because if that was the case, it should assume a constant value irrespective of the position in the examined zone on the radius. It should be emphasised here that the wood density of the near-pith and near-circumference zones of the trunk cross section is practically identical (Tab. 1), while MFA is significantly varying (Fig. 4). Its mean value in the near-circumference zone, in comparison with the near-pith one, is by 5.1 degree lower. In other words, at identical wood density, MFA reduction by 25 % leads to a corresponding average increase in wood as well as cell wall modulus of elasticity by about 50 %.

The mean value of the dynamic solid wood modulus of elasticity for all zones of the trunk cross section amounts to 12.1 GPa and corresponds to the mean value of the Scots pine modulus of elasticity determined in a bending test (Krzysik 1974, Wagenführ 2007). On the other hand, the mean of the dynamic cell wall modulus of elasticity is 38.6 GPa which is also in agreement with literature data (Ashby and Jones 1996).

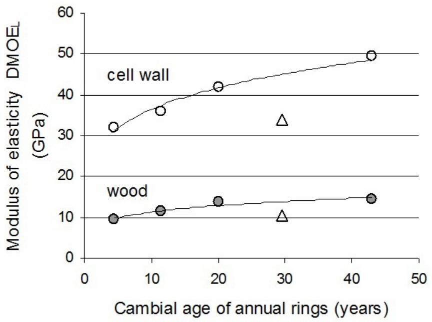

Fig. 7: Radial variation in the modulus of elasticity of Scots pine wood and tracheid cell walls. The trend lines are regression lines, for wood $y = 7.396x^{0,187}$, for cell walls $y = 23.213x^{0.196}$

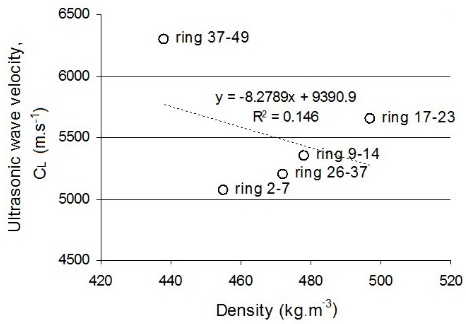

Fig. 8: Empirical relation between the modulus of elasticity of Scots pine wood and tracheid cell walls and the microfibril angle.

Fig. 8 shows the dependence of the wood tissue and cell wall modulus of elasticity on MFA. These dependences are negative and can be approximated by a linear function. Values of the determination coefficients indicate that MFA is responsible for about 74 % of variations in the analysed quantities. Also Yang and Evans (2003) investigating wood tensile strength found that MFA was responsible for variations in the modulus of elasticity to a higher degree than wood density. Yamashita et al. (2000) showed that variations in the modulus of elasticity cannot be attributed only to differences in wood density. Possible is also influence of fibre length correlated with the microfibril angle.

CONCLUSIONS

1. Propagation velocity of ultrasonic wave along the grain in pinewood (*Pinus sylvestris* L.) increases together with the wood tissue maturation and does not depend on wood density.

2. There is a clear negative correlation between the propagation velocity of ultrasonic wave along the grain in wood and microfibril angle. This dependence can be described by a linear function (R^2 = 0.71).
3. Modulus of elasticity of bulk wood as well as of wood cell wall increase together with the cambial age of annual rings. Variations in wood modulus of elasticity along the grain, at the same wood density, are determined by the microfibril angle. There is a clear negative correlation between wood as well as cell wall modulus of elasticity and microfibril angle. Variability of the wood and cell wall modulus of elasticity is in about 74 % determined by the microfibril angle.

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