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RELATIONSHIP BETWEEN LENGTHWISE ULTRASOUND TRANSMISSION AND TRACHEID LENGTH IN WOOD OF SELECTED SOFTWOOD SPECIES

Jan Raczkowski, Lidia Helińska-Raczkowska, Waldemar Moliński

Department of Wood Science,
The August Cieszkowski Agricultural University of Poznań

SYNOPSIS. The effect of the tracheids length on the lengthwise ultrasound transmission rate in the wood of coniferous species has been studied. The study has been performed for the samples of 12 tree species characterised by the tracheid length from 2 mm for yew tree and juniper to about 7 mm for araucaria.

KEY WORDS: ultrasound velocity, lengthwise, softwood, tracheid length

INTRODUCTION

Ultrasound transmission in wood has been studied for over 150 years, since the publication of the pioneer work by WERTHEIM and CHEVANDIER (1846). In the last decade the interest in this area of study has increased. The study has been focused on recognition of the character of ultrasound transmission in wood in the aspect of the application of this method for evaluation of wood and wood products quality (STEIGER 1991, SANDOZ 1993, GREUBEL and PLINKA 1995, KOLESNIKOVA 1996, HAN 1996, NIEMZ et AL. 1997, SCHOB et AL. 1997, MARĆOK et AL. 1997). A problem of particular interest is the effect of the tracheid length on the ultrasound transmission rate in the lengthwise direction. The problem has not been comprehensively studied yet. Some authors have been concerned with intra and inter-species relationships between the ultrasound transmission rate along the fibres and the length of anatomical elements of wood. Among the works on intra-species relationships, Dzbeński and Szymański (1976) reported a high linear correlation ($r = 0.92$) between the ultrasound transmission rate along the fibres and the length of tracheids in pine wood (*Pinus sylvestris* L.). Equally high ($r = 0.90$) correlation was reported by Polge (1984) between the ultrasound transmission rate and the length of fibres in *Prunus avium* L. wood. Niemz and Aguilera (1995) studied inter-species relationships between the ultrasound transmission rate along the fibres and the length of tracheids in wood samples of five coniferous species from Chile and reported linear correlations between the parameters studied but characterised by a low correlation coefficient for deciduous species ($r = 0.60$) and very low one ($r = 0.39$) for coniferous species.

In view of the above reports it seems interesting to perform a comprehensive study analysing the relationship between the ultrasound transmission rate and the length of wood anatomical elements as the hitherto published results have only signalled the problem without solving it. Thus, a study was undertaken to check the relationship between the tracheid length changing in a possibly widest range and the ultrasound transmission rate along the tracheids for selected coniferous species.

METHODS

Selection of wood samples

The samples to be studied represented 12 coniferous species of the expected range of the tracheid length changes from 2 mm (yew) to about 8 mm (araucaria) (Wagenführ and Scheiber 1974). The samples were obtained from the stock of the Department of Wood Science, Agricultural University, Poznań, except for the wood sample of araucaria given by the Institute of Wood Technology, Poznań. The wood was obtained from the trees growing in Poland, except the sequoia – from a plantation in the Great Britain and araucaria from trees grown in Australia.

Experimental procedure

The length along the fibres of the samples studied varied from 30 to 150 mm and the size of their cross-section varied too. In the samples containing a significant part of the tree trunk, the measuring heads were mounted in the near-pith, intermediate and circumferential zones. The moisture content of the samples measured varied from 8 to 10%.

The time of the ultrasound wave propagation through the samples was measured by a material testing device type 543, made by Unipan in Łódź, Poland. The emitting head 05T20 and the receiving head 05R20 worked at the frequency of 0.5 MHz. The measurements were performed in the vertical arrangement (Fig. 1) in order to ensure a permanent and possibly stable contact between the measuring heads and the front surfaces of the samples. To improve this contact the front surfaces of the samples were covered with silicon oil. The time of the ultrasound wave

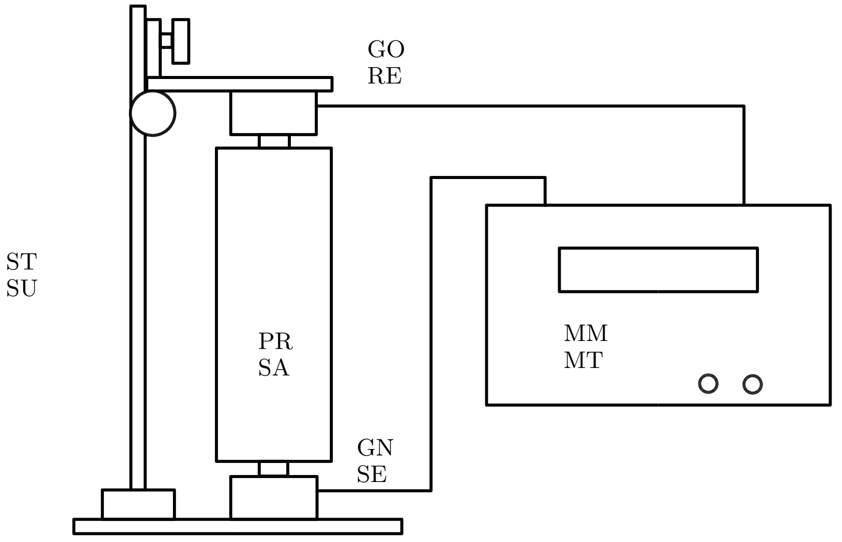

Fig. 1. Scheme of the test device for ultrasound transmission rate measurement along the fibres: SU – support, SE – sender, RE – receiver, SA – wood sample, MT – microsecond timer

Rys. 1. Schemat układu do pomiaru przenikania ultradźwięku w drewnie wzdłuż włókien: ST – statyw, SE – głowica nadawcza, RE – głowica odbiorcza, SA – próbka drewna, MT – mikrosekundowy miernik czasu

transmission was measured to the accuracy of 0.1 µs. The ultrasound propagation rate was calculated from the relation:

$$C_L = \frac{L}{t} \ \ \text{(m/s)}$$

where: L (m) is the length of the sample and t (s) is the time of the ultrasound wave passing through the sample.

The length of tracheids was measured in the samples covering the annual rings localised in the middle of the site at which the head was placed during the ultrasound transmission rate measurements. The wood samples in which the tracheid length was to be measured were subjected to maceration in a mixture of ice acetate acid and oxygenated water H_2O_2 (30%) used at the 1:1 ratio. The maceration was performed at 60°C for 30 hours. The macerates were dyed by water-alcohol solution of safranine. In each sample the lengths of 30 tracheids were measured: 15 early ones and 15 late ones. The lengths of the tracheids in the short-tracheid species were measured by a digital image analyser using the software "Imal", while those of the long-tracheid species were measured in the slides using a slide projector with the measuring rule scaled in micrometers. The slides were projected onto a screen in which they were measured by a measuring rule to an accuracy of 10 µm.

RESULTS AND DISCUSSION

Results of the ultrasound wave transmission rate along the fibres in the wood of the species studied are given in Table 1. The numbers of the samples are accompanied with the names of the zones of annual rings covered by the head on measurements. In each annual ring zone the measurement was repeated twice. The values given in Table 1 are means of the two measurements. The ultrasound wave transmission rate measured along the fibres changes from 4.5 km/s for yew wood to 6.6 km/s for araucaria wood.

In order to assess the reliability of the results of ultrasound transmission rate, in Table 2 they are given together with earlier reported values of this parameter available in literature. As follows from this comparison, our experimental results for coniferous species in general agree with the literature data. Therefore, it is assumed that our results have satisfactory accuracy. No data on the ultrasound wave transmission rate along the fibres have been found in literature for the following species: *Taxus baccata* L., *Juniperus communis* L., *Thuja plicata* D. Don., *Abies grandis* Lindl, *Araucaria bidwillii* Hook, and *A. cuninghamii* Sweet.

The accuracy of the measurements of the tracheid lengths was also satisfactory as the variation coefficient was 10.2 (3.2-16.7)%. The length of the tracheids in the wood of the species studied varies from 1.5 mm for juniper to 7.8 mm for araucaria. In individual samples the lengths of tracheids depend on the annual ring zone in which they are measured. In the tree trunk cross-section the shortest tracheids occur in the near-pith zone (Sanio 1872). In farther rings the tracheid length reaches a maximum and then remains at a constant level or slightly decreases. Table 3 presents the experimentally determined lengths of tracheids for the coniferous species together with the analogous data reported in literature, as follows from the comparison, our results in general agree with the literature results. The relationship between the ultrasound wave transmission rate along the fibres and the lengths of tracheids is shown in Figure 2. This relation has been defined for all the data from Table 1. As follows from the relation, with increasing length of tracheids, the ultrasound transmission rate along the fibres increases, however, the scatter of the results is considerable. For instance, interestingly, the ultrasound transmission rate for juniper wood, characterised by the mean tracheid length smaller than that of yew wood, is greater. The relationship is linear but characterised by a relatively low correlation coefficient ($r = 0.413$). When the calculations are made for the mean values of the ultrasound transmission rate in particular classes of the tracheid lengths every 500 µm, the correlation coefficient increases to $r = 0.480$.

The correlation coefficients characterising the relationships between the ultrasound transmission rate and the tracheid length are higher than those reported by Niemz and Aguilera (1995) for different coniferous species from Chile.

The results of our study have shown that the use of the ultrasound transmission rate measurements along the fibres for estimation of the length of tracheids, does not bring reliable values because the correlation coefficient characterising the correlation between these two parameters is rather low. It should be emphasised that the intraspecies correlation between these parameters is stronger (Dzbeński

Table 1. Lenghwise ultrasound velocity (C_L) and tracheids length (L_C) of various softwoods species
Tabela 1. Podłużna prędkość przewodzenia ultradźwięku (C_L) i długość cewek (L_C) różnych gatunków iglastych

Wood species Gatunek drewna	Sample number Numer próbki	Increments zone from pith Strefy przyrostów rocznych od rdzenia [years – lata]	Ultrasound velocity Prędkość ultradźwięku C_L [m/s]	Tracheids length Długość cewek L_C [mm]
1. *Taxus baccata* L.	1	21-57	4 454	2.19 ±0.35
	2	50-81	4 462	2.65 ±0.35
	3	53-81	4 631	2.39 ±0.18
	4	×	4 315	2.27 ±0.26
2. *Juniperus communis* L.	1	1-14	4 840	1.90 ±0.22
	2	4-34	5 851	2.12 ±0.23
	3	5-34	5 870	2.16 ±0.28
	4	7-34	5 816	2.18 ±0.25
	5	×	4 895	1.85 ±0.22
3. *Thuja plicata* D.Don.	1	3-8	5 546	2.31 ±0.23
	2	12-23	5 975	2.40 ±0.31
	3	42-57	4 668	2.37 ±0.24
4. *Abies alba* Mill.	1	×	6 098	3.63 ±0.37
	2	×	6 105	3.65 ±0.58
5. *Abies grandis* Lindl.	1	2-8	5 764	2.93 ±0.41
	2	18-25	6 143	3.92 ±0.66
	3	41-64	6 415	3.10 ±0.40
6. *Pinus sylvestris* L.	1	1-5	4 877	2.63 ±0.49
	2	27-41	5 698	3.51 ±0.49
	3	77-99	5 986	4.87 ±0.36
7. *Picea abies* (L.) Karst.	1	3-21	6 240	3.90 ±0.29
	2	25-32	6 194	3.85 ±0.41
	3	56-71	6 146	3.99 ±0.57
8. *Larix decidua* Mill.	1	1-6	5 093	2.81 ±0.37
	2	3-8	5 586	3.22 ±0.28
	3	20-40	6 339	3.67 ±0.42
	4	30-42	5 751	4.52 ±0.44
	5	56-70	6 444	4.56 ±0.26
	6	60-68	5 048	3.90 ±0.41
9. *Pseudotsuga menziesii* Franco	1	2-6	5 279	3.38 ±0.18
	2	23-31	5 606	4.23 ±0.39
	3	49-60	5 462	4.64 ±0.16
10. *Sequoia sempervirens* End.	1	10-12	4 720	4.60 ±0.36
	2	14-18	5 015	5.10 ±0.30
11. *Araucaria bidwillii* Hook.	1	×	4 897	5.82 ±0.52
	2	×	5 180	5.82 ±0.52
12. *Araucaria cunninghamii* Sweet.	1	×	6 550	7.04 ±0.48
	2	×	6 597	7.04 ±0.48

× – increment zone was not identified.
× – stref przyrostowych nie oznaczono.

Table 2. Comparison of investigated wood ultrasound velocity values parallel to fibres (C_L) with values from literature
Tabela 2. Porównanie prędkości ultradźwięku wzdłuż włókien (C_L) w drewnie badanych gatunków iglastych z danymi z literatury

Wood species Gatunek drewna	Ultrasound velocity (C_L) Prędkość ultradźwięku (C_L)		
	according to authors' data według danych autorów	according to data from literature według danych z literatury	
	[km/s]		
Taxus baccata L.	4.5 (4.3-4.6)	–	
Juniperus communis L.	5.5 (4.8-5.9)	–	
Thuja plicata D. Don.	5.4 (4.7-6.0)	–	
Abies alba Mill.	6.1	4.6-5.5	(WERTHEIM and CHEVANDIER 1846, STEIGER 1991)
Abies grandis Lindl.	6.1 (5.8-6.4)	–	
Pinus sylvestris L.	5.5 (4.9-6.0)	3.3-6.0	(WERTHEIM and CHEVANDIER 1846, BURMESTER 1965, DZBEŃSKI and SZYMAŃSKI 1976, BUCUR 1988, STEIGER 1991)
Picea abies (L.) Karst.	6.2 (6.1-6.2)	4.8-5.7	(BURMESTER 1965, BUCUR 1980, SANDOS 1989, KOLESNIKOVA 1996, MARĆOK et AL. 1997)
Larix decidua Mill.	5.7 (5.0-6.4)	5.0-6.5	(MOLIŃSKI and FABISIAK 2002, FABISIAK et AL. 2003)
Pseudotsuga menziesii Franco	5.4 (5.3-5.6)	4.7-5.5	(BUCUR 1980, NIEMZ and AGUILERA 1995)
Sequoia sempervirens End.	4.9 (4.7-5.0)	5.2	(NIEMZ and AGUILERA 1995)
Araucaria bidwillii Hook.	5.0 (4.9-5.2)	–	
Araucaria cunninghamii Sweet.	6.6	–	

and SZYMAŃSKI 1976, POLGE 1984). A more comprehensive explanation of the mechanism of the ultrasound wave propagation along the fibres in wood samples would require an experimental study of the effect of the microfibriles inclination angle in the S_2 of the secondary cell wall. According to a recent opinion the angle of the microfibriles inclination in S_2 of the cell wall is one of the main determinants of the wood rigidity and even its general quality (BUTTERFIELD 1998).

Table 3. Comparison of investigated wood tracheids length values (L_C) with values from literature
Tabela 3. Porównanie długości cewek (L_C) w drewnie badanych gatunków iglastych z danymi z literatury

Wood species Gatunek drewna	Tracheids length (L_C) Długość cewek (L_C)		
	according to authors' data według danych autorów	according to data from literature według danych z literatury	
	[mm]		
Juniperus communis L.	2.1 (1.5-2.8)	–	
Juniperus sp.		1.1-2.4	(Panshin and de Zeeuw 1980)
Taxus baccata L.	2.4 (1.7-3.1)	–	
Taxus brevifolia Nutt.		2.3	(Panshin and de Zeeuw 1980)
Thuja plicata D. Don.	2.4 (1.9-3.2)	3.2	(Panshin and de Zeeuw 1980)
Abies alba Mill.	3.6 (2.5-4.4)	2.6-4.6	(Huber and Prütz 1938, Wagenführ 1989)
Abies grandis Lindl.	3.6 (2.3-4.9)	3.0-3.5	(Panshin and de Zeeuw 1980)
Pinus sylvestris L.	3.7 (2.2-5.6)	1.4-4.4	(Huber and Prütz 1938, Laurow 1973, Dzbeński and Szymański 1976, Wagenführ 1989)
Larix decidua Mill.	3.8 (2.2-5.3)	2.3-4.3	(Huber and Prütz 1938, Wagenführ 1989)
Picea abies (L.) Karst.	3.9 (2.7-4.9)	1.7-5.0	(Huber and Prütz 1938, Wagenführ 1989)
Pseudotsuga menziesii Franco	4.1 (3.0-5.0)	3.0-4.5	(Panshin and de Zeeuw 1980, Wagenführ 1989)
Sequoia sempervirens End.	4.9 (4.0-5.7)	5.8	(Panshin and de Zeeuw 1980, Wagenführ 1989)
Araucaria bidwillii Hode.	5.8 (4.9-6.5)	–	
Araucaria cunninghamii Sweet.	7.0 (5.7-7.8)	–	
Araucaria sp.	–	5.6-9.0	(Wagenführ and Szeiber 1974)

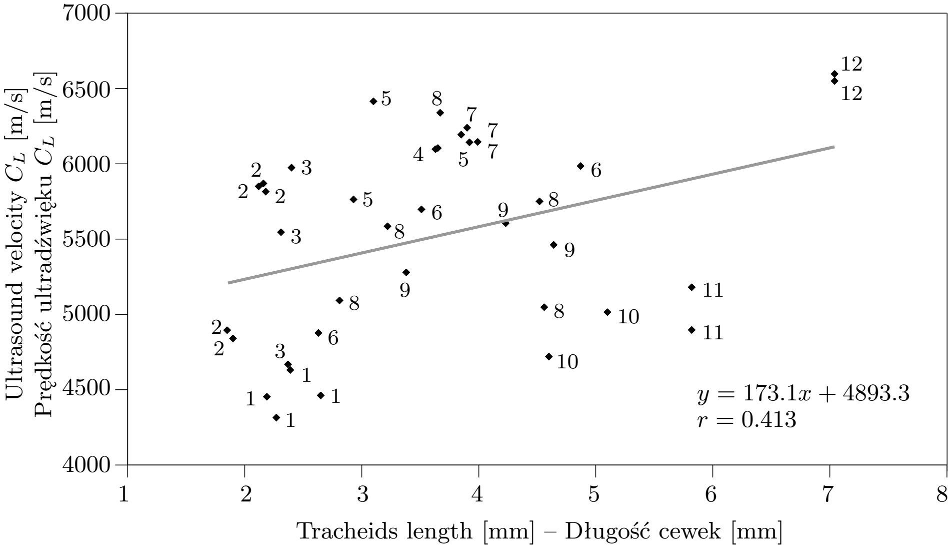

Fig. 2. Relation between the ultrasound wave transmission rate along the fibres (C_L) and the tracheid lengths in wood samples of various softwoods species (numbers refer to the position of a given species in Table 1)
Rys. 2. Zależność między prędkością ultradźwięku wzdłuż włókien (C_L) i długością cewek różnych gatunków iglastych (numery odpowiadają nazwom gatunków w tabeli 1)

CONCLUSIONS

1. With the mean tracheid length in the wood of the species studied increasing from 2.4 mm for yew tree to 7.0 mm for araucaria, the ultrasound transmission rate along the fibres increases from 4.5 km/s to 6.6 km/s.
2. The relation between the ultrasound transmission rate along the fibres and the length of tracheids for the species studied is linear but characterised with a low correlation coefficient ($r = 0.413$-0.480).
3. Estimation of the mean tracheid length in the wood of the species studied on the basis of the ultrasound transmission rate measurements along the fibres is unreliable because of the low correlation coefficient.

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ZALEŻNOŚĆ MIĘDZY PRĘDKOŚCIĄ ULTRADŹWIĘKU WZDŁUŻ WŁÓKIEN I DŁUGOŚCIĄ CEWEK WYBRANYCH GATUNKÓW IGLASTYCH

Streszczenie

Badano zależność między długością cewek i prędkością ultradźwięku wzdłuż włókien w drewnie 12 gatunków iglastych.

Przy zróżnicowaniu średniej długości cewek w drewnie badanych gatunków od 2,4 mm dla cisa do 7,0 mm dla araukarii prędkość ultradźwięku wzdłuż włókien zwiększa się odpowiednio od 4,5 km/s do 6,6 km/s. Zależność między prędkością ultradźwięku wzdłuż włókien i długością cewek różnych gatunków ma charakter prostoliniowy przy niskim jednakże współczynniku korelacji (r = 0,413 ... 0,480).

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Authors' address:
Prof. dr hab. Lidia Helińska-Raczkowska
Prof. dr hab. Waldemar Moliński
Katedra Nauki o Drewnie
Akademia Rolnicza im. Augusta Cieszkowskiego w Poznaniu
ul. Wojska Polskiego 38/42
60-627 Poznań
Poland