WOOD RESEARCH
61 (3): 2016
413-422

RESONANCE WOOD MICROSTRUCTURE PECULIARITIES

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(Received June 2014)

ABSTRACT

In researches there are contradictory conclusions about interconnection between macrostructural and acoustic characteristics of sounding timber. Unfortunately, there are only a few works of such kind and all of them are of sporadic nature, which give evidence of necessity to continue such researches both at the level of macrostructure and microstructure.

The aim of the research is to reveal the peculiarities of sounding timber microstructure, thanks to which it combines two incompatible, at first sight, parameters: High modulus of elasticity (rigidity) and low density. As a result, sounding timber differs from ordinary one in its unique acoustic characteristics, especially in delicacy and timber of sounding.

The research results were obtained through applying an electronic scanning microscope to 360 constant and temporary specimens. For this purpose, 800 timber cuts were made in transversal, radial and tangential directions of a tree stem. Besides, macerated material was used to define early and late tracheids length.

In the course of the experiment the increment layers width, the number of tracheids in a radial row of early wood, the number of tracheids in a radial row of late wood, the radial and tangential diameters of early and late tracheids, the thickness of tracheids radial and tangential walls in early and late wood, the quantity of vertical resin ducts and their diameter, the height and number of plies in linear (single-row) rays, the height and number of plies in fusiform rays, the diameter of a horizontal resin duct, the quantity and diameter of rounded bordering pores on tracheid walls were studied.

The research results revealed a number of differentiating characteristics of sounding spruce timber microstructure.

KEYWORDS: Sonorous spruce, annual ring, microstructure elements, structural features of sounding timber.

INTRODUCTION

The data concerning the microstructure of resonance wood, contingence of its acoustic radiation properties with physic-mechanical parameters are extremely poor. At early stages of studying this problem, researchers considered resonance properties of softwood to be due to its rather simple and ordered anatomic structure. The basic part of volume of such wood is represented by tracheides that are highly extended fibers with sclerotic walls. They were confusingly assigned the role of extended strings resounding against musical instrument sounds.

Some researchers attributed acoustic properties of wood to wood rays, spruce having them more than 4,000 per sm^2. It was the abundance of this anatomic element that was considered a favorable attribute of resonance wood (Kuznetsov 1930).

Kuznetsov (1930) assumed that spruce from various areas of growth had various fiber length, wall thickness of tracheides, amount and development of wood rays, so acoustic properties of timber would also be different.

The author also points out that unusability of other wood species for manufacturing decks, though they have high elasticity (for example, birch, beech, etc.), is connected with the fact that they do not have clearly expressed year rings as spruce does.

One of the fundamental works executed by Russian scientists is research into microscopic structure of resonance wood of Norway spruce from Chuvash woods (the Volga region of Russia). (Aturina 1937) determined the following distinctive features of resonance wood of high quality spruce:

- elasticity modulus and density of timber do not depend on the percentage of basal areas of tracheides cavities and walls;
- minimum elasticity modulus (at the given average density of wood) is connected with low lignin content in cellular walls and, hence, with less lignifying of them;
- minimum content of lignin is observed in the samples with great amount of bordered pits on tracheides radial walls;
- the thickness of cell walls of late tracheides is approximately 2 times higher than the thickness of corresponding walls of early tracheides.

The conclusion made by the author is rather interesting and important. She states that distinguishing resonance wood is only possible through combining microscopic and macroscopic methods of diagnostics.

Layrand and Yatsenko-Khmelevsky (1981) studied the role of a late zone in the formation of sounding properties of Norway spruce growing in Karelia woods (Northern region of Russia). The authors determined that acoustic properties of spruce timber are higher when the specific volume of late zone solid volume exceeds the volume of cavities of late tracheides. For example, in the 1-st grade samples the total thickness of cell walls of late tracheides averaged 64 %, and the total size of their lumens was about 36 %, when in the samples of the lowest grades those were 49 and 51 % accordingly.

According to the data presented, the authors attributed priority acoustic significance to the macrostructure of a growth layer late zone, but in their research they did not take into account either the content of earlywood in general, or its acoustic role.

Among the important modern works in the field of anatomy of resonance wood there are the studies Arganashvili (1974) on the examples of Oriental spruce and Caucasian fir. The basic conclusions of work are as follows:

- the dynamics of annual ring width fluctuation (0.5-4.5 mm for Oriental spruce, 0.5-5.0 mm for Caucasian fir) causes changes in density and elasticity module only; the ratio of these parameters does not affect the size of an acoustic constant significantly;
- the content of latewood affects greatly, first of all, the density and elasticity module of the material given, but when its share in the structure of annual ring exceeds 35 %, the value of an acoustic constant drops sharply.

Modern scientists abroad attribute resonance wood properties, first of all, to its anatomic structure peculiarities, namely, interpermeability of cell systems located along and across the tree stem axis, i.e. tracheides and woodrays. Tracheides size, density and membrane and pores thickness, position of micelles in cell walls, ratio of early and late tracheides, capacity to form lignin, degree of purity from pitches and other organic substances are considered from these view points.

Here the works of Ille (1978, 1979) could be highlighted. He presented rather extensive information on biological and technical features of resonance wood in manufacturing violins by Italian masters of XVII-XVIII centuries.

A well-known law is in the basis of new theory of resonance wood quality. It says, that although sound conductivity remains an important property, internal friction which should be low (not to interfere with sound propagation), as well as the speed of attenuation of fluctuations which, on the contrary, should be high (in order that the tone faded quickly allowing the new one arising on a string replace it) are decisive for a given material. Due to such combination clearness of sound and tone quality are supported.

Internal friction and attenuation of fluctuations in timber are caused by the set of small, microscopic and submicroscopic cavities and apertures filled with air. They do not raise friction, but maintain attenuation of fluctuations. Hence, apart from general technical requirements to resonance wood (ratio of high elasticity module to low density) the presence of a definite volume of empty apertures in timber to maintain low internal friction and high attenuation of fluctuations is necessary.

The amplitude of fluctuations and thus the amount of the energy radiated in a sound field from decks are connected basically to cross-section waves which, as well as longitudinal waves, depend not only on configuration and size of a deck, but, first of all, on the structure of wood. Hence, this is one more weighty proof that the skill of a master consists in the ability to choose the thickness and the corresponding form of the resonant board depending on the wood structure, which meets the requirements to sound intensity and reverberation characterizing the quality of a musical instrument.

Spruce wood having rather simple and homogeneous structure is notable for the fact that significant part of it (up to 70 %) is represented by the cavities filled with air, whereas firm substance of cellular walls falls within only 30 % of volume.

The principal condition for high acoustic quality of this wood species, in Ille's opinion, is that wood had more permeable pores-"colons", especially in early tracheides which sound waves pass along both in longitudinal and in cross-sectional directions and penetrate into the board across the entire thickness.

Thus, the above information confirms the timeliness of spruce resonance wood microstructure studies.

MATERIAL AND METHODS

The material for research is represented by spruce wood harvested in the plantings of the Murashinskiy timber enterprise of the Kirov region (the zone of southern taiga of Russia). 180-200 year old test trees were taken from three sites in mature forest stands of average productivity; the forest type is wood-sorrel - ferns spruce grove (Fedyukov 1998).

The region belongs to the component of introregressive hybridization, therefore Norway spruce in the pure state does not practically occur here, it can be found more often in hybrid forms with properties common to both Norway and Siberian spruce.

Standard samples sized 20x20x300 mm (with a long side going along fibers) were made of 20 modeling trees at breath height according to the requirements of GOST (All-union Standard) 16483.31. After keeping them in dry room environment for 2 years complex research was done on defining basic physical and dendro-sonorous properties of timber such as humidity, density, macrostructure, and speed of ultrasound propagation. The measurements sequences of dendro-sonorous properties measurement are presented in Fig. 1 C sound propagation speed in timber was measured with UK-14 p pulse ultrasound device through measuring τ time of longitudinal elastic wave propagation along l sample length:

$$C = l / \tau \tag{1}$$

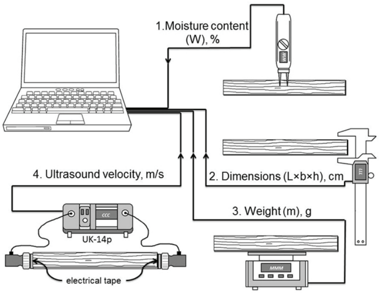

Fig. 1: Principle diagram of experimental measurements.

It is important to note, that there was a 60 Hz piezoelectric transducer used in the device, which is most appropriate for timber study (Nikishov and Shapochkin 1971).

Sound propagation speed in the material and its density given, it is possible to define E Young dynamic modulus of elasticity, considering the following (Ugolev 2001):

$$C = \sqrt{\frac{E_{dyn}}{\rho}}, \quad \text{then} \quad E_{dyn} = C^2 \cdot \rho. \tag{2}$$

It is well known that the value of K sound propagation constant suggested by Andreyev (1938) is taken as a main criterion of material musicality in many countries.

$$K = \sqrt{\frac{E}{\rho^3}} \tag{3}$$

Note: for sounding timber $K \geq 12$ $m^4/ kg \cdot s$ is a threshold value.

In total 186 samples were processed. Ten samples were selected from two groups contrasting in sound propagation constant ($K > 12$ and $K < 12$ $m^4g^{-1}s^{-1}$) based on year ring width and layers equality, late wood percentage in them, density and elasticity. Such a technique of sample selection is due to the task in view consisting in, firstly, comparing at a micro level the best (*K*> 12 m^4/kg^{-1}s^{-1}) and the worst (K <12 m^{4}g^{-1}s^{-1}) timber as sonorous material; secondly, revealing the contingence of acoustic and some physic and mechanical properties with anatomic structure.

Specimens from the spruce cuts were prepared according to the technique accepted in xylotomy for light microscopy (Yatsenko-Khmelevski 1954). To study timber with an electronic scanning microscope, the thickest cuts (0.2-0.3 mm) were made, pasted to little stages, gold sprayed and photographed.

Wood macerating was carried out by Nekhludova's original technique through long (2-3 hours) boiling in a weak solution of nitric acid, which allowed to reduce to minimum the influence of processing on thin structures of cytoderm. To get macerate fast the boiling in Schultze mixture was applied (strong nitric acid and a small crystal of potassium chlorate).

The total number of constant and short-term preparations made is 360 (about 800 cuts).

Cross-section cut measurements: width of growth layer, number of tracheides in a radial line of earlywood; number of tracheides in a radial line of latewood; radial and tangential diameter of early and late tracheides; thickness of radial and tangential walls of tracheides in early and latewood; quantity of vertical resin ducts and their diameter.

Tangential cut measurements: height and ply-rating of linear (one-row) rays; height and number of rows of fusiform rays; diameter of a horizontal resin duct.

Radial cut measurements: quantity and diameter of rounded bordering pores on tracheide walls.

The length of early and late tracheides was measured in macerated material.

RESULTS

Overall, 26 anatomic attributes were selected for the analysis of timber with high and low sonorous parameters, 21 most significant ones for sonorous timber acoustics being presented in Tab.1.

Tab. 1: Comparative analysis timber with different sounding characteristics.

№	Name of characteristics	Unit	Timber with high sounding characteristics					Timber with low sounding characteristics				
			X	X_{min}	X_{max}	±r	V (%)	X	X_{min}	X_{max}	±r	V (%)
1	Annual ring width	mm	2.1					2.4				
2	Percentage of autumn timber in annual ring	%	17.9					24.4				
3	Number of annual rings in 1 cm	pcs./cm	4					4				
4	Number of tracheids in radial line of spring timber	pcs.	46.3	45	48	0.39	2.7	49.2	38	64	2.95	18.94
5	Nature of transition zone between spring and autumn zones in annual ring	-	drastic					gradual, smooth.				
			19.4	15	25	1.20	19.62	23.7	12	39	3.11	41.49

6	Size of radial space of spring tracheid	um	33.4	25.9	44.1	2.02	19.18	20.1	18.6	22.3	0.79	15.89
7	Size of tangential space of spring tracheid		18.8	17.2	20.5	0.05	14.82	2.9	2.0	3.7	0.35	8.47
8	Thickness of radial wall of spring tracheid		2.9	2.3	3.2	0.06	9.15	2.7	2.3	3.2	0.07	11.79
9	Thickness of tangential wall of spring tracheid		2.1	1.6	2.6	0.13	19.76	4.5	3.7	5.0	0.15	12.56
10	Size of radial space of late tracheid		5.8	5.0	6.9	0.06	14.12	16.2	15.0	19.7	0.47	21.57
11	Size of tangential space of late tracheid		14.2	12.9	15.3	0.14	21.58	5.5	4.9	5.8	0.11	13.53
12	Thickness of radial wall of late tracheid		7.1	6.5	7.9	0.06	8.33	8.9	5.5	8.1	0.17	8.59
13	Thickness of tangential wall of late tracheid		5.4	4.9	6.5	0.16	9.50	2.0	1.5	2.9	0.15	24.15
14	Height of single (linear) ray	um	189.7	85.1	318.2	17.56	41.39	9.0	6	16	1.16	49.87
15	Number of layers of single (linear) ray	-	10.1	4	17	0.05	42.72	19.6	18.1	22.5	0.79	34.72
16	Height of one cell of single (linear) ray	um	18.8	12.6	23.9	0.79	39.19	6.1	4	8	0.37	23.69
17	Dimension of single (linear) rays	%	5.2	2	8	0.35	26.41	491.1	255.2	709.1	45.66	29.40
18	Height of fusiform ray	um	510.7	285.1	729.2	35.41	31.01	1.5	1	9	0.07	17.06
19	Dimension of fusiform rays	%	1.3	I	5	0.14	40.83	7.6	4	15	0.75	38.46
20	Total dimension of radial parenchyma		6.5	2	12	0.53	37.62	63.4	55.8	72.7	2.40	11.98
21	Diameter of vertical resin channel	um	103.5	101.9	104.5	5.35	1.07	0.0	48.0	107.1	5.75	28.39

Judging from these research results it is possible to conclude, that high-quality sounding spruce timber in the given environment has some characteristic structural parameters:

- transition of early wood to late one is sharp; if the transition zone is present, its width should not exceed 8-10 % of width of an early zone of a year ring (the transitive zone included);
- early tracheids, tetragonal or hexagonal in cross-section, with membrane thickness of 2.0-3.2 microns are located in even regular rows, i.e. radial populations;
- evenly decreasing radial dimension of tracheids in a radial population;
- rectangular or square in cross-section late tracheids with membrane thickness 2.0-2.5 times exceeding early tracheids wall thickness;
- long even early tracheids (on average, 3.2-3.5 mm) with bordered pores regularly located in one-two rows on their radial walls;
- long even late tracheids (on average, 3.5-4.5 mm) without pores in the walls;
- high even single-row rays (average linear dimension is 189-190 microns) with oval-shaped cells elongated along the trunk axis and having approximately the same size;
- high even fusiform rays (average length is 510-520 microns);
- very poor accompanying parenchyma; the ratio of late tracheids solid volume to overall solid volume of cellular walls should not exceed 40 %; the ratio of late tracheids solid volume to year ring overall area size should not exceed 15 %.

DISCUSSION

It is known, that macrostructure is the basic diagnostic attribute of quality of resonance wood, i.e. the width of its annual rings and content of late wood in them. These parameters are authorized by corresponding standards of many countries, so fine-grain wood with the width of annual rings of 1-4 mm and late wood content no more than 30 % is used for manufacturing musical instruments.

Meanwhile, such properties of wood macrostructure were not a general rule for masters manufacturing musical instruments long ago. For example, old German violin masters generally used very fine-grain wood, while Amati brothers, as well as Andrea Guarneri, chose coarse-grained wood (Vitachek 1964).

Thus, macrostructure is not the only diagnostic attribute of resonance wood, which was paid attention to not only by masters but by scientists as well (Atourina 1937, Ille 1978, 1979).

The results provided confirm and complement the results of research done by other authors in earlier studies of resonance wood microstructure.

Defining the acoustic role of the size and character of a transitive zone in an annual ring is considered the most significant result of the work under discussion. In practice, it means that when selecting resonance wood it is necessary to take into account, alongside with other standard requirements, the following parameters: transition of earlywood into latewood should be sharp, “unblurred”; and “the transitive zone” should not exceed 8-10 % of width of an annual ring early zone.

It should be specially noted, that width of annual rings modulus influences acoustic parameters of spruce wood insignificantly. More essential role here belongs to specific distribution of late tracheides. High resonant properties of wood are reached, as a rule, if the zone of late tracheides in annual rings will not exceed 20 %.

A good confirmation of practical importance of this statement is the fact that Stradivari and other old Italian masters made the basic acoustic radiating element for their unique violins, the sound board, from wood with similar structure.

It is also ascertained that there is a positive relation between the quality of resonance wood and linear size of radial rays (single-row and fusiform), whereas the quantity of rays per unit area as well as their total amount do not influence the acoustic parameters significantly.

In recent years scientists of many countries have heightened interest in wood microstructure in relation to its physical-mechanical properties. There appeared research papers devoted to the studies of wood structure and density dependent on elasticity (Danihelova and Čulik 2013), correlation between anatomic structural elements and physical properties of spruce and pine wood in longitudinal and cross-section directions (Fabisiak 2005, Rajčan 1990), empirical model for tangential and radial width of fibers in annual rings of spruce wood (Ille 1978), evaluation of durability of the walls of wood structure using nanotechnology (Ille 1997), automatic definition of fibrous structure of wood (Krauss and Kúdela 2011).

However, the modern data concerning the microstructure of resonance wood, correlation of its acoustic radiating properties with physical-mechanical parameters are extremely scarce. The big exception in this aspect is the research work devoted to the studies of ultrastructure and ultrasonic wave speed propagation in spruce resonance wood. In particular, it is established that low value of fibril angle influences the propagation of an ultrasonic wave along the fibers of spruce resonance wood (Bucur 2006, Danihelová 2004, Molinski and Marcinkowska 2007).

Not going into detail about the contents of these undoubtedly important scientific works, it should be noted, that they confirm, to a certain extent, and supplement the scientific data obtained by us and other authors in the process of earlier researches on sonorous timber microstructure. For example, in their fundamental work Bulgarian scientists G. Blskova and N. Brdarov prove that alongside with other peculiar features of macro- and microstructure, the factor of transition zone from early to late wood in a year ring is highly significant for formation of acoustic properties of sonorous spruce (Blsková and Brdanov 2003).

CONCLUSIONS

The results obtained confirm that there are certain peculiar features of the microstructure of sounding timber due to which 'musical' wood differs from regular one in unique acoustic properties, especially in delicacy and timber of sounding.

For the practice of selecting this unique natural material with the aim of manufacturing a qualitative musical instrument, it is important to take into account, alongside with the standard range year rings width (1.0-4.0 mm), one more characteristic attribute. In a year ring, the transition of early wood into late one is sharp. If the transition zone is present, its width should not exceed 8-10 % of width of an early zone of a year ring (the transitive zone included).

It should be noted, that research into the timber microstructure is rather labor consuming and difficult. However, without this research it is impossible to understand the process of unique acoustic properties formation in this valuable natural raw material, and, just as important, to take a step closer to solving the mystery of Stradivari secret.

REFERENCES

1. Andreyev, N.N., 1938: On the tree for musical instruments. Collection of works, CMSRI. M.L., 1:11-18.
2. Arganashvili, L.N., 1974: Wood eastern spruce and Caucasian fir as raw resonance. The dissertation of the candidate of biological sciences. Tbilisi, 35 pp.
3. Atourina, N.V., 1937: Study of the microscopic structure of the resonant spruce (*Picea excelsa* Link) with regard to its technical features: The Dissertation of the candidate of technical sciences. - St. Petersburg., 60 pp.
4. Blskova, G., Brdarov, N., 2003: Sounding wood acoustic characteristics studies. Collection of scientific reports 50th anniversary of the Forest Engineering Institute, Woodworking and furniture production section, Sofia. Pp 49-53.
5. Bucur, V., 2006: Acoustics of wood. Springer Verlag, Berlin, Heidelberg, 393 pp.
6. Danihelova, A., 2004: Relevant physical acoustics of spruce wood as a material for musical instruments. Proceedings of the 8th World Conference on Timber Engineering wcte. 2004, Lahti, Finland. Pp 491- 494.
7. Danihelova, A, Čulik, M., 2013: Non-traditional use of mountain ash for production of viola elements. In Noise and vibration in practice: Proceedings of the 18th International Acoustic Conference. Bratislava: Slovak Technical University in Bratislava. Pp 27-30.
8. Fabisiak, E., 2005: Variability of the basic anatomic elements and wood density in selected wood species. Poznan. Applied Science Rozprawy Naukowe No. 369 (in Polish).
9. Fedyukov, V.I., 1998: Spruce resonance: Selection on the vine cultivation, certification. Scientific publication. Yoshkar Ola Mar STU, 204 pp.

10. Ille, R., 1978: Processing and properties of resonance wood for production of violins. Drevo 33: 133-138.
11. Ille, R., 1979: The use of resonance wood of spruce for production of violins. Drevo 34: 303-304.
12. Krauss, A., Kúdela, J., 2011: 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. Wood Research 56(4): 479-488.
13. Kuznetsov, I.I., 1930: Resonant wood and deck, forestry and timber industry. Pp 42-44.
14. Layrand, N.E., Yatsenko-Chmielewski, A.A., 1981: Some anatomical features of the structure resonant wood. Modern problems of Wood Science, Voronezh. Pp 45-47.
15. Moliński, W., Marcinkowska, A., 2007: Interrelationships between macrostructural parameters of pine (*Pinus sylvestris* L.) wood and the propagation velocity of ultrasound waves in the direction along fibers. Drewno 50(177): 79-89.
16. Nikishov, V.D., Shapochkin, A.S., 1971: Non-destructive testing of wood for musical instruments. In: Proceedings of the All-Union Conference on Contemporary Problems of Wood Science. Minsk. Pp 87-89.
17. Rajčan E., 1990: Die Physikalisch – akustischen Charakteristiken von Holz als Material fur die Production von Streichinstrumenten. In: Latest achievements in research of wood structure and physics. Zvolen: Vysoka skola lesnicka a drevarska vo Zvolene. Pp 56 - 62.
18. Ugolev, B.N., 2001: Wood-forest with the basics of merchandising. Moscow State Forest University, 340 pp.
19. Vitachek, E.F., 1964: Essays on the history of manufacture of stringed instruments. Moscow: Music, 341 pp.
20. Yatsenko-Khmelevski, A.A., 1954: Bases and methods of anatomic study of timber. M-L., AS USSR, 335 pp.

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