Optimization of Spruce (*Picea abies* L.) Wood Thermal Treatment Temperature to Improve Its Acoustic Properties

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The study was undertaken to establish the thermal treatment parameters of spruce (*Picea abies* L.) wood that would ensure the highest possible value of the specific modulus of elasticity (E/ρ) and, thus, the best acoustic performance. The basic acoustic parameters of spruce wood were determined prior to and after its thermal treatment. As a result of thermal treatment, the samples density slightly decreased by about 1%, irrespective of temperature applied. The average value of Young modulus of the samples after modification at 120 to 160 °C increased from 10.1 to 10.7 GPa (6%). The specific modulus of elasticity increased on average by 6.5%. Increase of the modification temperature to 180 °C resulted in decreasing of the values of mechanical parameters by over 4%.

Keywords: Spruce; Specific modulus of elasticity; Acoustic parameters; Thermal modification

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INTRODUCTION

Although wood from a few species is used to construct musical instruments, the upper boards of resonance boxes are usually made of spruce wood (Kamiński and Świrek 1972). In stringed instruments, wood is used to enhance the sound of strings by the phenomenon of resonance. The wood suitable for this purpose is characterized by small logarithmic decrement (Mania *et al.* 2017) and as high as possible specific modulus of elasticity (Bucur 2006), defined as the ratio of E/ρ. The acoustic parameters used to evaluate resonant wood quality for the construction of stringed instruments, including violins, are velocity of sound propagation ($V = \sqrt{(E/\rho)}$), acoustic impedance ($Z = \rho\sqrt{(E/\rho)}$) and acoustic constant ($A = \sqrt{(E/\rho^3)}$). The modulus of elasticity and density appear in all acoustical parameters describing the suitability of wood for production of resonance boards. It is convenient to use the specific modulus of elasticity (E_{sp}) as an indicator of good quality resonant wood. The best resonant wood should have a high value of modulus of elasticity (E) and a low density of approximately 400 kg/m^3 (Bucur 2006).

The choice of thermally modified wood for construction of stringed musical instruments follows from its properties. Such wood is characterized by decreased density and reduced hygroscopicity, which improve the dimensional stability of the instrument. During thermal modification of wood, its density decreases, and after a relatively mild treatment, its linear modulus of elasticity and hardness may increase (Viitaniemi *et al.* 1997; ThermoWood® Handbook 2003; Boonstra *et al.* 2007; Windeisen *et al.* 2009). The decrease in density as a result of thermal modification is related to evaporation of side components of wood, such as terpenes, fat, wax, and phenols that evaporate and the products of decomposition of the least stable hemicelluloses. A significant reduction of hemicelluloses—the most hydrophilic component of wood—leads to a considerable decrease in hygroscopicity of the modified wood, through reduces the contribution of hydroxyl groups (OH) that are responsible for binding water (Kollmann and Fengel 1965; Moliński *et al.* 2010; Moliński *et al.* 2016). The above-mentioned changes caused by thermal modification of wood could improve its acoustic parameters, *i.e.*, sound velocity, acoustic impedance, and acoustic constant. Therefore, it can be expected that proper choice of thermal treatment temperature may increase the value of E/ρ and improve the acoustic performance of wood. Moreover, the literature provides reports on attempts at diminishing of the wood inhomogeneity and improving the ratio of the elasticity modulus to density (E/ρ) (Nagyvary *et al.* 2006; Spycher *et al.* 2008; Schwarze *et al*. 2008; Stoel and Borman 2008).

In this study, the intention was to experimentally select the parameters of thermal modification at which the highest value of the specific modulus of elasticity (E_{sp}) would be obtained, thus improving the acoustic parameters. Therefore, the basic mechanical parameters of wood before and after its thermal treatment were determined in the tests.

EXPERIMENTAL

Materials and Methods

The study was performed for eight radially cut planks from spruce wood of different suitability for resonance boards. The specimens were obtained from trees growing in the Eastern Romanian Carpathians near Maramureș, which produce high quality resonant wood (Bielczyk and Bobrowicz 1960). All planks were classified by luthiers to three groups of resonant wood quality, classes I, II and III, according to BN-70/9221-06 (1970). The planks were also characterized by different widths of annual rings and different latewood percentage.

Physical and mechanical properties were determined for wood samples of the size 10 (radial) × 10 (tangential) × 150 (longitudinal) (mm^3) obtained from each plank and conditioned at 20 °C and a relative humidity (RH) of 50 ± 2% for 2 months. The cutting method is illustrated in Fig. 1.

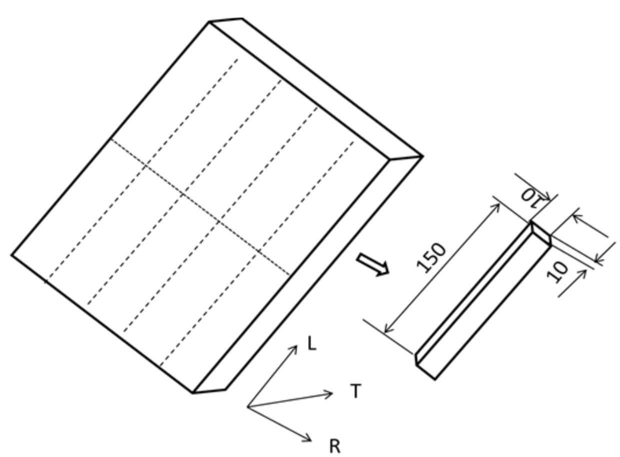

Fig. 1. The way of sample preparation

The sample density was determined according to ISO 13061-2 (2014). The mass of each sample was measured on an analytical balance (Sartorius GmbH, Goettingen, Germany) (± 0.001 g accuracy). The dimensions were measured with a digital caliper to the accuracy of ± 0.01 mm. The moisture content of the samples varied from 8.5 to 9.2%.

The modulus of elasticity of the samples (10 × 10 × 150 mm^3) was measured in a static bending test after conditioning (20 °C, 50% RH). The bending force direction was tangent to the annual rings, and its value was 120 N. This value was established in preliminary studies performed on 15 samples subjected to full bending test, until damage, reading off the force value at the border of proportionality. The bending of samples with the force smaller than that at the border of proportionality does not result in permanent deformation, so it was possible to use the samples again for measurements of the elasticity modulus after modification. The tests were performed on a universal mechanical strength testing machine (Zwick Z050TH, Ulm, Germany) prior to and after sample modification. The distance between the supports during the test was 120 mm, while the load was placed exactly in the middle between the supports. The rate of loading was chosen in such a way to complete the test in about 90 s.

The test machine output was used to calculate the modulus of elasticity, according to Eq. 1,

$$E = \frac{\Delta F \, l^3}{4 \, \Delta f \, a \, h^3} \text{ (MPa)} \tag{1}$$

where ΔF is the load difference (N), Δf is the increment of the sample deflection (mm), a is the sample width in radial direction (mm), and h is the sample height in tangential direction (mm).

The specific modulus of elasticity was defined as follows,

$$E_{sp} = E/\rho \text{ (kNm/kg).} \tag{2}$$

where ρ is the wood density.

Basic acoustic parameters were calculated on the basis of the relevant physical parameters. The sound propagation velocity (V) was calculated from the formula:

$$V = \sqrt{\frac{E}{\rho}} \text{ (m/s)} \tag{3}$$

Acoustic impedance was defined as,

$$Z = V \times \rho = \rho \times \sqrt{\frac{E}{\rho}} \text{ (kg/m}^2\text{s),} \tag{4}$$

and acoustic constant as:

$$A = \sqrt{\frac{E}{\rho^3}} \text{ (m}^4\text{/kgs).} \tag{5}$$

After determination of the E, the samples were subjected to thermal modification in a steam atmosphere, based on the ThermoWood procedure (Viitaniemi *et al.* 1997; González-Peña and Hale 2007; Boonstra 2008; Moliński *et al.* 2010). Different variants of wood modification were carried out in laboratory conditions at 120 °C, 140 °C, 160 °C, and 180 °C, which were applied for 3 h. At first the planks were heated to achieve a temperature of 110 °C in their bulk. The temperature was maintained for 2 h to get wood moisture content at a level of about 1%, then the temperature was increased to a desired value and maintained for 3 h. After completion of heating at a constant temperature, the heating was turned off. After the decrease of temperature, the influx of steam was stopped and the planks were kept in the chamber until their temperature reached that of the ambient. Each variant of modification was applied to 30 samples representing the three quality groups, with 10 samples in each class. The average density and macrostructural parameters of all samples were similar in each variant. After modification, the density and modulus of elasticity of all samples were measured. The samples were conditioned under the same conditions before and after modification, but the processes taking place in wood, mainly at 180 °C, reduced the equilibrium moisture content (EMC) of the wood. Mechanical parameters of wood to a high degree depend on the moisture content, so they were determined at the same EMC. For this reason, the samples subjected to modification at 180 °C were conditioned in a desiccator in the presence of $NaNO_3$ (20 °C, RH= ~ 70%), which ensured that the moisture content of these samples was approximately 8.5%. Prior to modification, the moisture content of the samples varied from 8.5 to 9.1%, while after modification it ranged from 8.3 to 8.8%.

The experimental data were analyzed using the Dell™Statistica™13.1 software with the analysis of variance (ANOVA). Significant differences between mean values of the parameters describing the properties of treated and untreated samples were determined using Tukey’s HSD test. The comparison tests were performed at a 0.05 significance level.

RESULTS AND DISCUSSION

An important feature for wood classification with regard to its suitability for musical instruments is the equality of its annual rings (Table 1). In the samples classified as resonance wood, the annual rings widths varied from 1.21 mm to 1.91 mm. The deviation between the maximum and minimum annual ring width were also different for different classes. Narrower rings were noted for class I (0.8 mm), while the widest were observed for class III (1.4 mm).

Table 1. Macrostructural Parameters of Spruce Wood

Quality Class	Macrostructure	Mean	Min.	Max.	Standard Deviation	Coefficient of Variation V (%)
I	rw	**1.21**	0.85	1.67	0.26	21.5
	lwp	**15.0**	8.5	17.4	2.74	18.3
II	rw	**1.48**	0.98	2.02	0.33	22.3
	lwp	**19.6**	9.2	26.7	5.12	26.1
III	rw	**1.91**	0.97	2.41	0.48	25.1
	lwp	**25.2**	12.8	28.8	4.30	17.1

Note: rw, ring width (mm), lwp, the latewood percentage (%)

In addition to the uniform width of annual rings, the resonance wood should show poorly developed latewood. The basic statistical data on these parameters are given in Table 1. The most uniform material was wood of class I. The difference between the maximum and minimum contribution of latewood was only 9%.

It is generally assumed that with increasing width of annual rings in coniferous species, the percentage of latewood decreases (Kollmann and Cóte 1984), but in the material studied the reverse was true. The smallest contribution of latewood was noted in the wood of the narrowest annual rings. The reason for this difference can be difficult growth conditions for the trees supplying the wood. The wood from high-mountain spruce trees is characterized by poorly developed latewood. Because of the short vegetation period, the wood shows narrow annual rings of poorly developed latewood, which is desired in good quality resonance wood. The latewood percentage below 20% is characteristic of good resonance wood (Holz 1984). Spycher *et al.* (2008) observed that in some high quality resonance wood the latewood is made of only 4 to 6 tracheids in the radial direction of a ring.

Figure 2 presents the histograms of density distribution in the wood from each class. The wood from class I showed the lowest density in the range 380 to 430 kg/m^3, and in class II wood the density varied from 410 to 460 kg/m^3. In class III, the density varied from 520 to 580 kg/m^3. The above differences are directly related to the above-discussed macrostructural parameters of annual rings, mainly to the latewood percentage. In all samples studied, the density distribution was similar to normal, with the expected value (mean) μ and variance σ^2, which is often denoted as N(μ; σ^2) (Fig. 2).

The sample density slightly decreased as a result of thermal treatment, which confirms earlier reports (Gündüz *et al.* 2008; Gonzalez- Pena and Hale 2009). The mean values of wood density before (ρ) and after thermal treatment (ρ_{MOD}) are given in Table 2.

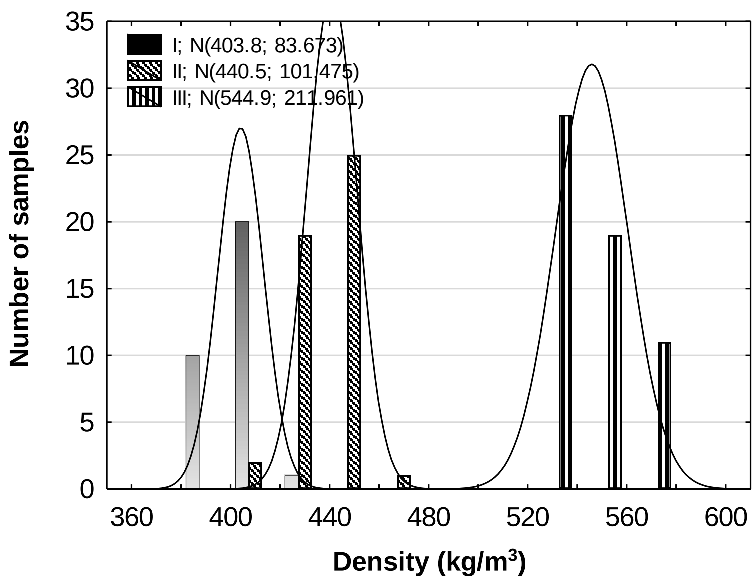

Fig. 2. Histograms of density distribution in individual quality classes of resonance wood

Table 2. Mean Value of Spruce Wood Density Prior to and After Modifications at Different Temperatures

Modification Temperature	Quality Class								
	I			II			III		
	ρ	ρ_{MOD}	$\Delta\rho$	ρ	ρ_{MOD}	$\Delta\rho$	ρ	$\rho_{MOD.}$	$\Delta\rho$
	(kg/m^3)		(%)	(kg/m^3)		(%)	(kg/m^3)		(%)
120 °C	405	396	-2.2	436	428	-1.8	545	540	-0.9
140 °C	404	398	-1.5	436	432	-0.9	544	537	-1.3
160 °C	405	400	-1.2	437	431	-1.4	545	536*	-1.7
180 °C	403	387*	-4.0	442	421	-4.8	543	529	-2.6

* Significant differences

The range of density change, $\Delta\rho$ was calculated as follows,

$$\Delta\rho = \frac{\rho_{MOD} - \rho}{\rho} \tag{6}$$

The thermal treatment at 120 to 160 °C caused a slight decrease in wood density, by about 1%, irrespective of the quality class. The treatment at 180 °C for the same time reduced the wood density on average by 3.4%, and the greatest density decrease, by almost 5%, was noted for wood of quality class II. The reduction of wood density as a result of its thermal modification was not a linear function of temperature. The ANOVA variance analysis was performed for the density changes of modified and unmodified wood representing the three quality classes. Although the arithmetic means of wood density before and after modification were different for the samples studied, according to the ANOVA analysis at the level of significance of 0.05, the differences were significant only for two variants. Thus, thermal modification of the resonance spruce wood at the applied temperatures may cause small changes in density. A decrease in the pine wood density by about 3.5% at 160 °C, has been described by *e.g.* Zawadzki *et al.* (2013), while Icel *et al.* (2015) after thermal modification of spruce wood at 190 °C have observed a decrease in wood density by about 3%. The decrease in density was found to be lower for spruce wood than for pine wood. This result can also be explained by the lower extractives content of spruce wood (Sehlstedt-Persson 2003).

As the wood density decreases upon thermal treatment, its mechanical parameters are expected to deteriorate. Table 3 presents the modulus of elasticity determined along the grains for the wood before (E) and after thermal treatment (E_{MOD}) at different temperatures.

Table 3. Mean Values of Modulus of Elasticity of Wood Samples Before and After Thermal Modification at Different Temperatures

Modification Temperature	Wood Quality Class								
	I			II			III		
	E	E_{MOD}	ΔE	E	E_{MOD}	ΔE	E	E_{MOD}	ΔE
	(MPa)		(%)	(MPa)		(%)	(MPa)		(%)
120 °C	7635	8236*	7.9	9767	10038	2.8	12838	13462	4.9
140 °C	7975	8494*	6.5	9561	10104*	5.7	13084	13747*	5.1
160 °C	7860	8424	7.2	9728	10225	5.1	12700	13307	4.8
180 °C	8109	7784	-4.0	10102	9669	-4.3	13004	12452	-4.2

* Significant differences

The thermal treatment at temperatures below 180 °C resulted in increasing values of the wood modulus of elasticity. The mean value of Young modulus after modification at 120 to 160 °C increased from 10.1 to 10.7 GPa (6%). Analysis of the changes in modulus of elasticity in particular classes of resonance wood quality revealed that the greatest increase in this parameter for the sample of the lowest density representing class I. This increase was 7.9% for the treatment at 120 °C, 6.5% at 140 °C, and 7.2% at 160 °C. After modification at 180 °C, the elasticity modulus decreased, and the decrease was close to 4.3%, irrespective of the wood quality class. An increase in the elasticity modulus upon modification at 190 °C has been confirmed by Navickas *et al.* (2015), who reported a growth of E by about 0.5%. A positive effect of thermal modification on the modulus of elasticity, not only of spruce wood, has been confirmed by *e.g.* Shi *et al.* (2007) and Kol *et al.* (2015). According to the ANOVA variance analysis, the differences in modulus of elasticity before and after modification were statistically significant in only four variants of modification. A statistically insignificant increase in the modulus of elasticity after thermal modification of spruce wood has been reported by Bekhta and Niemz (2003).

The modulus of elasticity values were analyzed as a function of wood density, before and after modification. The relationship between these two parameters for wood samples of similar moisture content are presented in Fig. 3.

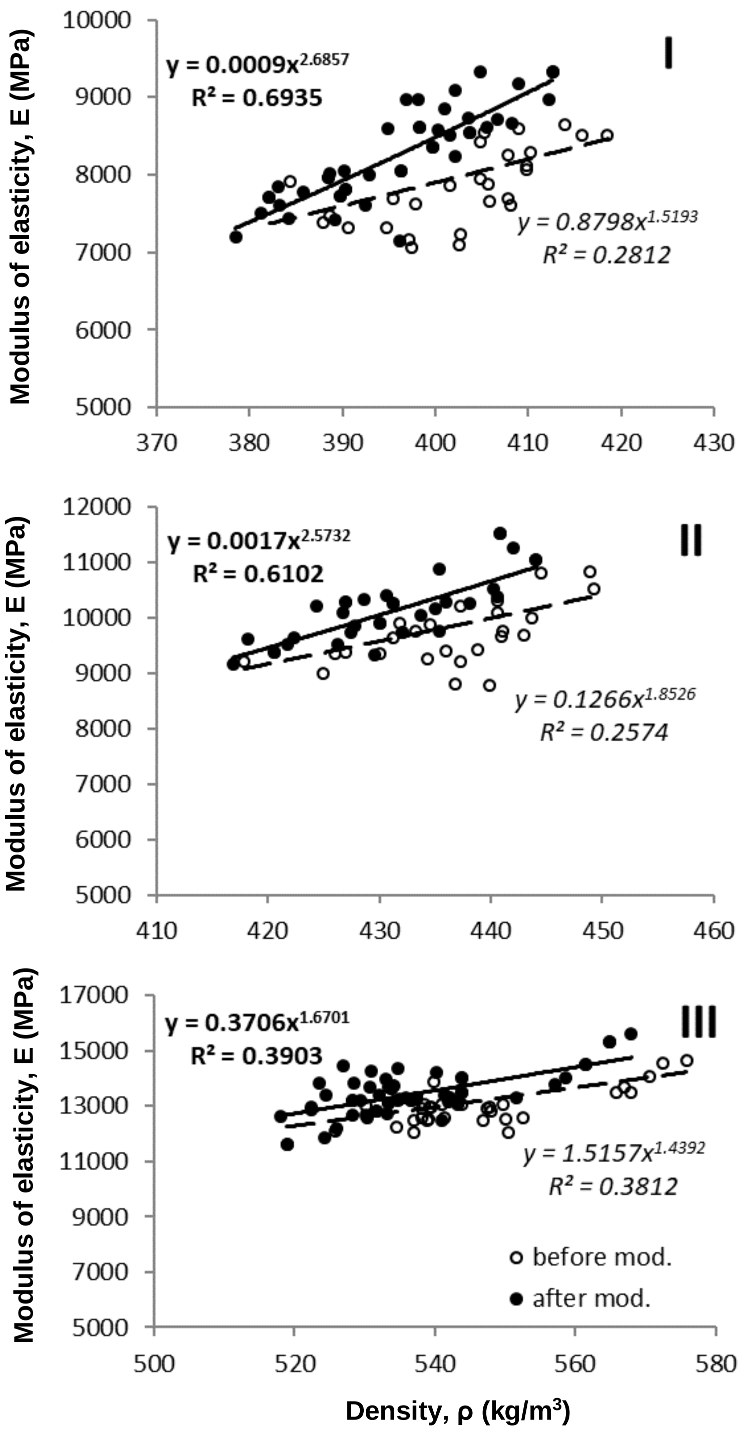

Fig. 3. Relationship between the modulus of elasticity and density of wood before and after its modification, for wood quality classes I, II, and III

Assuming that the power functions selected on the basis of the highest determination coefficient approximate these relations well, it can be concluded that the thermal modification resulted in clarification of the relationship between the modulus of elasticity and density of wood. This conclusion is supported by the fact that the coefficients of determination were higher for the modified than for unmodified wood. Thus it can be also concluded that thermal modification increased the uniformity of the wood samples. The greatest improvement in the quality of relationship between the modulus of elasticity and density was noted for wood representing classes I and II, *i.e*., for wood samples of lower density. Prior to the thermal treatment the modulus of elasticity values determined for these samples were much more scattered. Notably, the value of exponent n in the function $f(x) = x^n$ describes the relationship between the modulus of elasticity and density; it takes the highest value for wood samples representing class I (2.6857), lower for class II (2.5732), and the lowest for class III (1.6701). These values indicate that for the high quality resonance spruce wood, the relationship between the modulus of elasticity and density depends on other factors. The power function with the exponent of nearly 2.7 for samples in class I may indicate a significant impact of the microfibril angle (*MFA*) on the modulus of elasticity. Hence, the wood density is not the only determinant of its mechanical properties, as reported earlier (Raczkowski 1965; Zhang 1997; Roszyk *et al.* 2010; Krauss and Kúdela 2011; Roszyk *et al*. 2012; Fabisiak and Mania 2016). The impact of MFA is particularly pronounced for the wood of higher density, *i.e*., in latewood with smaller MFA values.

Good resonance wood is characterized by high modulus of elasticity at the lowest possible density. According to the results, the thermal modification of wood improved the ratio of these two parameters. The modulus of elasticity and density appear in all parameters describing the suitability of wood for production of resonance boards. It is convenient to use the specific modulus of elasticity defined as the ratio of E/ρ. The mean values of specific modulus of elasticity calculated for all samples are presented in Table 4.

Table 4. Mean Values of Specific Modulus of Elasticity of Wood Samples Studied Before (n.mod) and After Modification (mod.) at Different Temperatures

Modification Temperature	Quality Class								
	I			II			III		
	n.mod	mod.	$\Delta(E_{sp}/\rho)$	n.mod	mod.	$\Delta(E_{sp}/\rho)$	n.mod	mod.	$\Delta(E_{sp}/\rho)$
	(kNm/kg)		(%)	(kNm/kg)		(%)	(kNm/kg)		(%)
120 °C	18.87	20.80	10.2	22.41	23.40	4.4	23.54	24.92	5.9
140 °C	19.75	21.31	7.9	21.93	23.39	6.7	24.04	25.61	6.5
160 °C	19.39	21.04	8.5	22.23	23.74	6.8	23.27	24.84	6.7
180 °C	20.12	20.11	-0.05	22.86	22.97	0.5	23.95	23.54	-1.7

The mean values of specific modulus of elasticity before the modification for wood samples representing particular quality classes were 19.53, 22.36, and 23.70 kNm/kg. For the majority of variants, thermal modification increased the value of this parameter. The exception is the effect of thermal treatment at 180 °C, after which in wood samples of class I and II the value of specific modulus of elasticity remained practically unchanged, while in wood samples of class III it decreased by 2%. The greatest changes in the specific modulus of elasticity were found in the wood samples of the highest quality, for which E/ρ increased on average by 9% as a result of modifications at 120 to 160 °C. The corresponding increase in the E_{sp} for the samples of classes II and III after modification in the same conditions reached on average 6.5%. The greatest increase in the specific modulus of elasticity for the wood samples of all quality classes was noted at the modification at 160 °C, so the basic acoustic parameters were calculated only for this temperature of modification.

The results showed that thermal treatment at an appropriate temperature leads to an increase in the specific modulus of elasticity and thus improves all other acoustic parameters. Table 5 presents the acoustic parameters of the resonance spruce wood of different classes of quality, calculated for the modification temperature of 160 °C. Also the percentage differences (Δ) between the acoustic parameters before and after modification are included.

Table 5. Mean Values of Sound Velocity (*V*), Acoustic Impedance (*Z*), and Acoustic Constant (*A*) of Wood Samples Studied Before (n.mod) and After Modification (mod.) at 160 °C

Acoustic Parameter	Quality Class								
	I			II			III		
	n.mod	mod.	Δ	n.mod	mod.	Δ	n.mod	mod.	Δ
V (m/s)	4400	4584	+4.18	4714	4872	+3.35	4820	4982	+3.36
Z (kg/ m^2*s)*10^5	17.84	18.35	+2.86	20.62	20.98	+1.75	26.30	26.96	+2.51
A (m^4/kg*s)	10.86	11.46*	+5.52	10.78	11.32*	+5.01	8.84	9.30*	+5.20

* Significant differences

Analysis of the data presented in Table 5 justifies the distinction of the wood studied in the quality classes. High quality resonance wood should be characterized by the lowest possible acoustic impedance and the highest possible acoustic constant (Bucur 2006).

Thermal modification at 160 °C brought about an increase in all basic acoustic parameters of the resonance spruce wood. The greatest differences were observed in the acoustic constant, which after thermal treatment had been increased by about 5.2%. Only the differences in this parameter were statistically significant for wood of all quality classes. The acoustic constant determines the wood suitability for construction of resonance musical instruments, and for good resonance wood it should be higher than 10. The increase by about 3.6% was found for the sound velocity. The smallest changes were observed in the acoustic impedance increased as a result of heat treatment by about 2.4%, which is beneficial for the resonance wood, as it does not affect the damping of vibrations of particles and sound wave (Holz 1973). What is more, in first class wood, the greatest increase in the acoustic parameters was noted.

Similar observations have been reported by Pfriem *et al.* (2007) who studied the effects of modification of spruce wood. Mohebby *et al.* (2007) have reported an improvement in acoustic parameters of modified wood of mulberry tree. Zauer *et al.* (2014) studied the effects of thermal treatment of beechwood at 140 °C and 160 °C, showing the improvement in its acoustic properties to the values characteristic of maple wood used for construction of elements of musical instruments.

CONCLUSIONS

1. The best improvement in the acoustic parameters for the spruce wood samples of all quality classes were achieved as a result of thermal modification at 160 °C. After this treatment the increase in the modulus of elasticity and acoustic constant was the highest.

2. Thermal modification can further improve acoustic parameters of the highest quality wood, which may bring even better acoustic performance of instruments made of it.

3. The use of thermally modified wood for construction of musical instruments is justified by the qualities of the modified product showing lower density and reduced hygroscopicity, which increases the stability of the instrument dimensions.

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