forests

Article

Physical and Acoustical Properties of Wavy Grain Sycamore Maple (*Acer pseudoplatanus* L.) Used for Musical Instruments

Florin Dinulica [1], Adriana Savin [2,3] and Mariana Domnica Stanciu [3,4,*]

[1] Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Transilvania University of Brașov, 500123 Brașov, Romania
[2] Institute of Research and Development for Technical Physics, B-dul Mangeron 47, 700050 Iasi, Romania
[3] Department of Mechanical Engineering, Transilvania University of Brașov, B-dul Eroilor 29, 500036 Brașov, Romania
[4] Russian Academy of Natural Sciences Sivtsev Vrazhek, 29/16, Moscow 119002, Russia
* Correspondence: mariana.stanciu@unitbv.ro

Abstract: The wood used in the construction of musical instruments is carefully selected, being the best quality wood from the point of view of the wood structure. However, depending on the anatomical characteristics of the wood, the resonance of wood is classified into quality classes. For example, sycamore maple wood with curly grains is appreciated by luthiers for its three-dimensional optical effect. This study highlights the statistical correlations between the physical and anatomical characteristics of sycamore maple wood and its acoustic and elastic properties, compared to the types of wood historically used in violins. The methods used were based on the determination of the acoustic properties with the ultrasound method, the color of the wood with the three coordinates in the CIELab system and the statistical processing of the data. The sycamore maple wood samples were divided into anatomical quality classes in accordance with the selection made by the luthiers. The results emphasized the multiple correlations between density, brightness, degree of red, width of annual rings, acoustic and elastic properties, depending on the quality classes. In conclusion, the work provides a valuable database regarding the physical–acoustic and elastic properties of sycamore maple wood.

Keywords: wavy grain sycamore maple wood; anatomical descriptors; acoustic properties; statistical correlation; musical instruments

check for updates

Citation: Dinulica, F.; Savin, A.; Stanciu, M.D. Physical and Acoustical Properties of Wavy Grain Sycamore Maple (*Acer pseudoplatanus* L.) Used for Musical Instruments. *Forests* **2023**, *14*, 197. https://doi.org/10.3390/f14020197

Academic Editor: Michele Brunetti

Received: 4 December 2022
Revised: 2 January 2023
Accepted: 17 January 2023
Published: 20 January 2023

1. Introduction

Over time, the practice of luthiers in using maple wood with wavy fibers for the back of violins has been transmitted to the present day. Since the acoustic quality of the violin is the synergistic result of several factors, it cannot be established whether the old luthiers preferred wavy maple wood for its acoustic characteristics or just for its aesthetic appearance. It is certain that researchers [1–3] discovered that the maple wood used by old luthiers, such as Guarnieri and Stradivari, was curly maple wood, but, as a result of aging and preservation treatments applied at that time, the curly maple wood these old luthiers used had very different chemical and acoustic properties when compared to the maple wood used to make modern musical instruments. Procuring this material is quite expensive and difficult because this growth defect is not only genetically produced but is the result of edaphic and climatic factors [4–6]. There are theories according to which the formation of wavy grain depends on the orientation of the cells in the cambium, but the development mechanism has not yet been fully explained. since the environment also contributes to the genetic factors, as shown in [7–9]. According to [10,11], the wavy grain in European sycamore maple wood is considered to be a "natural defect" that is optically observed in the radial direction, in the form of waves in the direction of the grain with respect to the longitudinal axis of the tree, and the pattern being an alternation of light and shadow stripes. North American sycamore and European sycamore maple trees exhibit differences are based on different growth mechanisms, as shown in [10]. The fiber pattern of European sycamore maple wood is natively produced by deviations from straight, regular grain [11–13]. Thus, the most common patterns of sycamore maple wood, resulting from the ability of the wood grain to capture and reflect light, are the following: curly grain, which gives the appearance of wavy waves, because it reflects light differently (Figure 1a); fiddleback, characterized by very frequent undulations, with a small distance between curly grains, used by luthiers in the construction of musical instruments (Figure 1b); flame grain, giving the effect of curls that roll like flames (Figure 1c); quilted grain resembles patchwork patterns (Figure 1d—upper part) and bird's eye, showing small, rounded, bright spots (Figure 1e) [9–12].

Figure 1. The common figures of sycamore maple wood: (**a**) curly grain; (**b**) fiddleback figure; (**c**) flame grain; (**d**) partial quilted grain; (**e**) bird's eye figure.

Regarding the degree of fiber curl, there are two approaches. The first approach is based on the angle, which highlights the presence of twisted fibers in standing trees, as presented by [9,10], and which is not the subject of our research, the material being collected from trees without apparent defects. The second approach, proposed by Alkadri et al., 2018 [14], is based on the measurement of wavelength, amplitude and grain angle measured in the transition point between peak and valley of the wave. In a previous article, [15], the angle of the fiber was measured according to the method proposed by Alkadri et al., 2018 [14], and an inverse proportional relationship between the wavelength and the curly grain angle was found. Starting from this conclusion, in the present paper we considered that the wavelength was sufficient to express the degree of undulation of the grain.

The current question posed by musical instrument manufacturers is whether having the wavy grain in the wood contributes to the acoustic quality of the musical instruments or has only aesthetic value. In this sense, various studies have been carried out on the physical, mechanical and elastic properties of the wavy-grain sycamore maple wood, but none provided synoptic information regarding the relationship between the pattern of the wood and its elastic and acoustic characteristics [14–18].

The acoustic quality of the musical instrument depends primarily on the acoustic and elastic properties of the material from which it is made; spruce wood for the top plate and wavy maple for the back. These properties are correlated with the physical characteristics of the wood species. Studies on the elastic, acoustic and dynamic properties of resonance wood (spruce and maple) have been the focus of many researchers, providing a rich source of data [9,11–18]. These studies investigated tone wood species from forest basins in Slovenia, the Czech Republic, Austria, Italy, France, Germany, USA.

Thus, related to physical and elastic features of sycamore maple wood, Sedlar et al. [4] reported longitudinal shrinkage, ranging between 0.13% and 0.28%, radial shrinkage, ranging between 3.2 to 5.2%, and tangential shrinkage, ranging between 7.2 to 10.9%, in comparison with straight maple wood reported on by Kollman [12] (longitudinal shrinkage 0.5%; radial 3% and tangential 8%). The density measured for specimens with 12% moisture content, varied from 0.52 to 0.73 g/cm^3 and modulus of elasticity at bending (MOE) recorded values between 6.1–11.3 GPa. Sonderegger et al. in paper [5] found a ratio of the dynamic modulus of elasticity on the three directions L:R:T of 9.8:1.7:1 and of the shear moduli in the shearing planes LT:LR:RT for 4.5:2.9:1. The studies highlighted the mechanical and acoustic properties of resonance wood (spruce and maple), identifying the values of sound propagation speeds in the longitudinal and radial directions, as well as the values of the modulus of elasticity through the following different methods to determine the resonance frequency [15–21]: the intrinsic transfer matrix method used to simulate the propagation of continuous waves or finite impulse in homogeneous, inhomogeneous or multilayered elastic media [16–19], and the non-destructive evaluation method based on ultrasound [22–27].

The research presented in this article aimed to highlight the correlations between the physical appearance of sycamore maple wood and its acoustic and elastic properties, taking into account the way luthiers select the raw material for musical instruments.

Thus, the study started from the hypothesis of the existence of correlations between the physical appearance of sycamore maple wood, including pattern of the wood and its acoustic/elastic properties. For this purpose, fiber undulation pitch of the sycamore maple grain and the color parameters, in terms of quality classes, were entered in digital format and correlated statistically with the following acoustic parameters determined by ultrasonic means: the speed of sound in the palm in the three main directions, the Young's modulus of elasticity, shear moduli and Poisson's ratios. The novelty of the research consisted in verifying the contribution of the wood structure to the acoustic performance of the sycamore maple wood from the Romanian Carpathian Mountains, known for the quality of its resonance wood. Data from the literature does not link the structure of the wood with its acoustic properties, and such studies on wood have not been reported until now.

2. Materials and Methods

2.1. Materials

In order to investigate the physical and mechanical properties, the samples of European sycamore maple wood (*Acer pseusoplatanus* L.) were extracted from types of wood specimens prepared for musical instruments. The specimens were obtained from logs of trees harvested from the Gurghiu area, in the Eastern Carpathian Mountains. The blanks had been naturally dried for a minimum of 3 years (straight grain maple wood used for school instruments) and up to 10 years for maestro instruments (the wavy grain sycamore maple). The specimens used in the tests were cut in the form of a cube, with sides of 40 mm, respecting the three main directions of the wood (radial, tangential, and longitudinal). The physical features of the studied samples are presented in Table 1.

Table 1. The physical features of the sycamore maple wood samples (Legend STDEV—standard deviation).

Physical Features	Grade/Average Value/STDEV							
	A	STDEV	B	STDEV	C	STDEV	D	STDEV
Wood density WD (kg/m^3)	609	3.022	601	4.381	594	8.494	623	16.308
Moisture content (%)	6.8	0.05	7.2	0.1	7.0	0.092	8	0.45

The samples were graded in four classes, denoted as A, B, C and D, in accordance with the classification of wood made by luthiers for the different quality classes of violins. Thus, the A class was considered the best wood maple, due to the wood pattern produced by the wavy grain, class B was also characterized by wavy grain, but rare, class C consisted of specimens with slightly wavy grain and class D had straight grain. The division of maple wood samples into the four quality classes, according to the intensity of the wavy grain, is also used by foresters, according to papers [13,15,23–26]. These categories related directly to the wood surface characterized by the wavy grain structure.

2.2. Methods

2.2.1. Color Measurement

Since the sycamore maple wood is optically sorted based on the macroscopic aspect of the structure, the color parameters were measured according to the CIELab system.

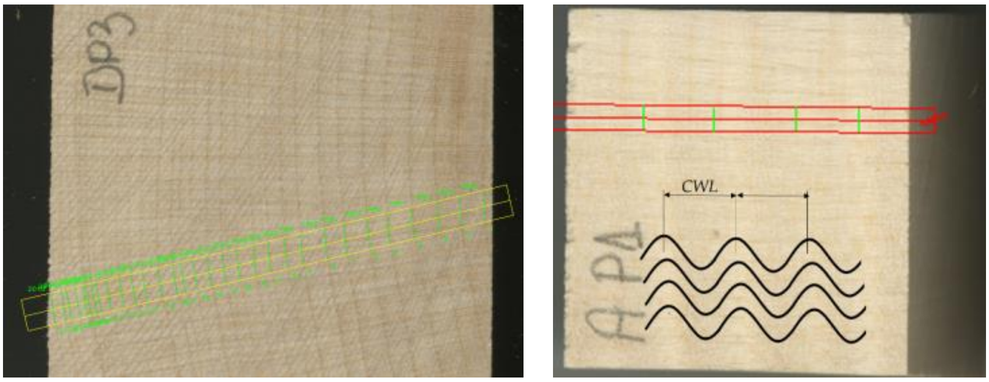
The measurements of color coordinates a* (the color redness/greenness), b* (the color yellowness/blueness) and L* (color brightness or whiteness) were carried out with a Minolta Chroma-Meter CR-400 (Konica Minolta, Tokyo, Japan) [24]. To measure the color parameters, 5 measurements were made on the diagonals of the radial section (from this, 30 measurements resulted, with 6 samples from each class).

2.2.2. Anatomical Features Measurement

Evaluation of the anatomical features of the sycamore maple wood was performed using the WinDENDRO Density image analysis system (Régent Instruments Inc., Québec City, QC, Canada, 2007). Each sample was scanned on its cross section and radial section in order to measure the width of the annual rings, denoted RW, and the fiber undulation pitch of the sycamore maple wood, denoted CWL, according to the method presented in studies [26–30]. In the references [12–17], wavelength was used, but in this study, the authors used the term fiber undulation pitch to differentiate the wavelength known in the acoustic field as the term used for undulation measurement.

Figure 2 shows how the anatomical characteristics of interest were measured for sycamore maple wood. The ring regularity index (RRI) was calculated using the mathematical relation (1), recommended by Dinulică et al., 2015 [29] for wood:

$$RRI = \frac{\max(RW_i) - \min(RW_i)}{\max(RW_i)} \tag{1}$$



(**a**) (**b**)

Figure 2. Measuring the anatomical characteristics: (**a**) the width of the annual rings on cross section; (**b**) fiber undulation pitch (CWL) on radial–longitudinal section.

2.2.3. Determination of Sound Velocity, Dynamic Elastic Moduli and Shear Moduli by Means of Ultrasonic Devices

The method of ultrasound measurements was presented in previous studies [17,24] and consisted of connecting the ultrasound sensors to the 5073 PR Pulse Receiver–Panametrics equipment [18]. A LeCroy Wave Runner 64Xi digital oscilloscope was used to visualize the signal and measure the propagation time in the wood samples. For each sample, measurements were made at five points on each face of the sample, which corresponded to the three planes of orthotropic symmetry of the wood (longitudinal–radial plane; tangential–longitudinal plane; and radial–tangential plane). The measurements were performed at a temperature of 24 °C and a humidity of 65%.

2.2.4. Statistical Evaluation

A large number of data were obtained, which were first analyzed under the aspect of variability. Using discriminant function analysis (DFA), the possibility of stratifying the values of the acoustic parameters according to the quality class of the sample was verified. DFA provides weights of predictor variables that reflect their ability to distinguish between groups of dependent variables [24,30–32]. The individual ability of acoustic variables to discriminate between quality classes was indicated by the magnitude of the partial Lambda parameter. Thus, the closer the value of the partial lambda parameter to 0, the greater the discrimination power. Normality of distributions was checked with the Shapiro–Wilk test. Relationships between acoustic parameters were verified by testing simple correlation coefficients. The association of the variables involved in the study was explored using Principal Component Analysis (PCA) and the k-means Clustering procedure, and then verified with simple and multiple correlations [29,32].

3. Results and Discussion

3.1. Anatomical Descriptors of the Sycamore Maple Wood

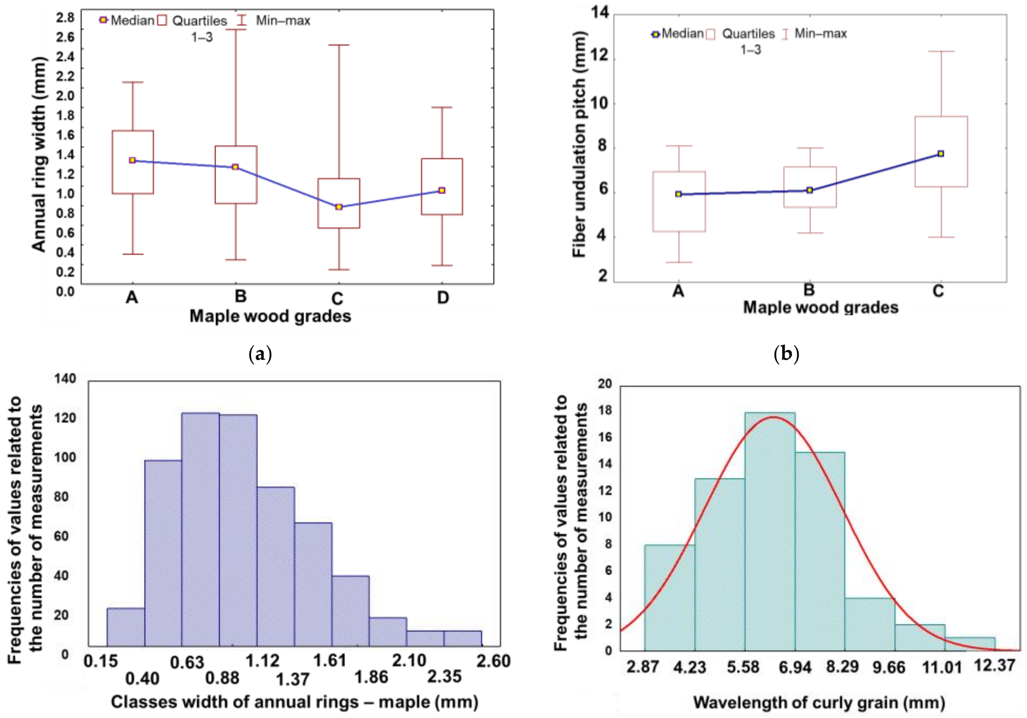
In the sycamore maple wood samples, the anatomical descriptors measured were the width of the annual rings (RW) and the pitch of the fiber undulation (CWL). It was found that RW was approximately 32% greater in the case of sycamore maple with wavy fibers (class A or B), compared to that with straight fibers (class C or D) (Table 2). According to studies [24,28], the higher the value of the regularity index (RRI), the lower the regularity of the rings. According to this hypothesis, it was observed that the RRI in sycamore maple wood was higher in wood with wavy grain than in wood with straight grain (Table 2). Among the ways of expressing the regularity of annual rings, the method of calculation that best reproduced the structural quality of the resonance wood was chosen in accordance with reference [24]. This rendered the regularity as a ratio between the amplitude of the variation (maximum value − minimum value) and the maximum value, a way of expression also used by other researchers. In Table 2, the regularity of annual rings is presented as a percentage value. In previous studies related to the anatomical characteristics of resonance wood in the construction of historical violins, average values of RW, in the range of 1.08–1.29 mm, were identified in historical violins, such as the Stradivarius Edler Voicu (1702), Leeb 1742; Klotz 1747, Babos 1920 and a Stainer Copy [3].

Table 2. Anatomical descriptors of the sycamore wood samples.

Anatomical Descriptors	Grade/Average Value/STDEV							
	A	STDEV	B	STDEV	C	STDEV	D	STDEV
Annual ring width RW (mm)	1.249	0.167	1.218	0.068	0.844	0.119	0.987	0.026
Regularity of annual ring width RRI (%)	76.574	5.838	80.028	5.700	82.932	5.872	83.462	6.045
Fiber undulation pitch CWL (mm)	5.448	0.460	6.2952	0.625	7.4182	1.400	NA	NA

It can be appreciated that the old luthiers chose sycamore wood taking into account these anatomical characteristics, something that was passed down from generation to generation among the luthiers. The use of sycamore maple with wavy fiber was also a tradition of luthiers, a fact proven by the analysis of the wave pitch of the fiber (CWL) both in historical violin boards and in the studied wooden samples. Thus, CWL in the back plates gravitates around the length of 5.7 mm for a Stradivarius Edler Voicu 1702 violin, 4 mm for a Stainer 1716 violin and 6.4 mm for Leeb 1742 violin, as highlighted by [3]. Compared with the values obtained in Table 2, it can be appreciated that the samples from class A described the best class of anatomical quality compared to the wood of heritage violins.

The determinations of the anatomical descriptors highlighted the fact that the width of the annual rings presented a high level of variability that encouraged the stratification of its values. The wavelength showed a moderate level of variability, but the range of values was quite wide (the amplitude of variation was 9.5 mm). The RW of the sycamore maple wood samples was not normally distributed (according to the Shapiro test W = 0.965, $p < 0.0001$), instead the CW was a Gaussian variable (W = 0.977, $p = 0.30$). Differences between samples were highly statistically significant with respect to annual ring width, but not confirmed with respect to CW. It was also found that in sycamore maple wood the tendency was to increase the width of the annual rings (Figure 3a) and to decrease the wavelength with improvement of the quality class (Figure 3b). It can be seen that class D is missing in Figure 2b because the length of the undulation pitch of the fiber in the case of samples from D grade tended to infinity, making it no longer possible to measure the pitch. In class C the range of values was greater. The width of the annual rings in the resonance paltin wood showed a pronounced asymmetry to the left for the size class 0.6–0.9 mm (Figure 3c), and the shape of the wavelength distribution was compatible with the normal law. The distribution module was in the size class 5.5–6.9 mm (Figure 3d). The small deviation revealed the homogeneity within the class and was the result of the way the luthiers selected the samples.



(**a**) (**b**)

(**c**) (**d**)

Figure 3. Variation of anatomical descriptors for resonance spruce in relation to the anatomical quality class: (**a**) the variation of the width of the annual rings; (**b**) Variation of the pitch of wavy fiber; (**c**) the distribution of RW; (**d**) distribution of CWL (red line–normal distribution).

3.2. Color of Sycamore Maple Wood Related to Anatomical Quality Classes

The stratification of the color, according to the quality grade, revealed the formation of two groups: one group was formed by classes A and D, and the other group was formed by classes B and C. Samples from classes A and D had darker wood ($L^* < 8.4\%$), with a high concentration of red ($a^* > 3.5$) and yellow in the color composition ($b^* > 17$) (Figure 4). Samples of quality classes B and C, had the highest brightness ($L^* > 84.5\%$). From the perspective of correlations with the other physical descriptors of maple wood, it followed that the density was inversely proportional to the width of the rings and the degree of red, but directly proportional to the wavelength and brightness. The relationship between ring width and sycamore maple wood color did not exceed the threshold of statistical significance. However, there was a tendency to increase the size of the red shade (a^*) and to temper the yellow shade (b^*) as the rings were wider. In conclusion, it could be appreciated that maple wood with curled and dense fiber was darker and had a higher degree of red and yellow in the color composition.

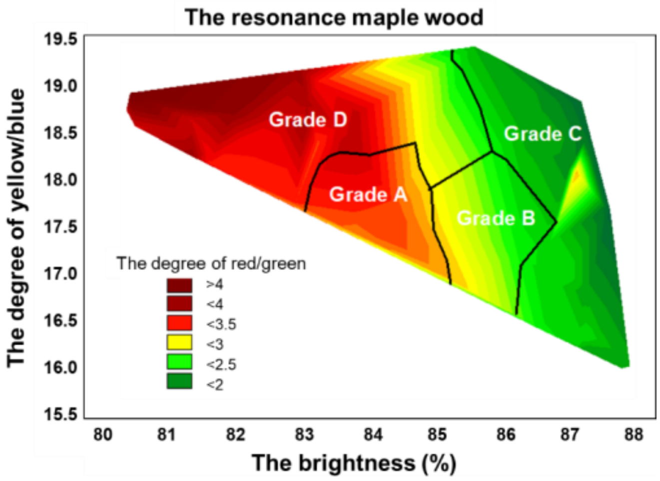


Figure 4. Multiple correlations between color parameters: brightness degree, yellowness degree and anatomical quality grade in sycamore maple wood.

3.3. Acoustic and Elastic Properties of Sycamore Maple Wood

The most important quantities that influence the acoustic quality of a musical instrument are the sound propagation speed, the elastic characteristics, the natural frequency, the respective quality factor, and the damping factor of the wood. Through the ultrasonic method used in this study, the sound propagation speeds in the three main directions of the wood, and its elastic characteristics, were determined, as shown in Table 3.

Table 3. The acoustic and elastic parameters of sycamore maple wood determined by ultrasound method.

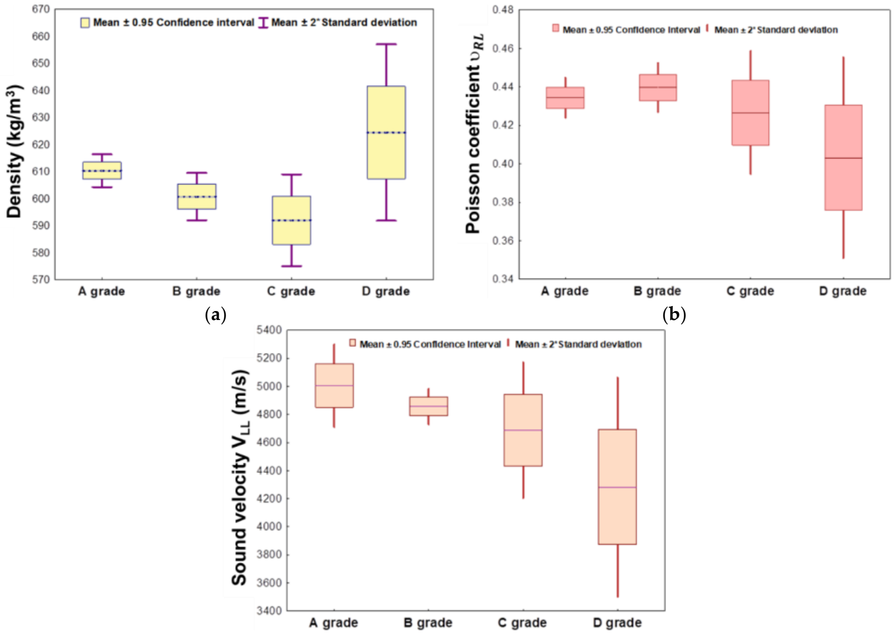
Type of Variables	Symbol	Grade of Sycamore Maple Wood Average Values			
		A	B	C	D
Density (kg/m^3)	$\overline{WD}$	610	601	592	624
Sound velocity in wood (m/s)	V_{LL}	4238	3820	3750	3925
	V_{RR}	1773	1896	1866	1808
	V_{TT}	1326	1392	1360	1359
The ratios of sound propagation speeds	V_{LL}/V_{RR}	2.39	2.015	2.009	2.17
	V_{LL}/V_{TT}	3.19	2.74	2.75	2.88
	V_{RR}/V_{TT}	1.33	1.36	1.37	1.33
Young's elasticity modulus (MPa)	E_L	10,968	8775	8359	9626
	E_R	1920	2030	2044	2044
	E_T	1074	1164	1096	1157
Specific longitudinal modulus of elasticity (GPa $*$ g^{-1} $*$ cm^3)	E_L/ρ	17.97	14.60	14.12	15.41
	E_R/ρ	3.14	3.38	3.45	3.27
	E_T/ρ	1.76	1.93	1.85	1.85
Shear Modulus (MPa)	G_{RT}	1259	1259	1259	1259
	G_{LR}	1648	1648	1648	1648
	G_{LT}	1560	1560	1560	1560
Specific shear modulus of elasticity (GPa $*$ g^{-1} $*$ cm^3)	G_{RT}/ρ	2.064	2.74	2.63	2.22
	G_{LR}/ρ	2.24	2.71	2.60	2.42
	G_{LT}/ρ	1.74	1.99	1.90	1.81
Poisson Coefficient	υ_{LT}	0.445	0.423	0.422	0.431
	υ_{LR}	0.394	0.335	0.331	0.365
	υ_{RT}	0.140	0.085	0.072	0.168

The obtained data were consistent with those identified in the specialized literature, even if the analyzed samples were extracted from trees harvested from Romanian forests. Thus, the values determined by Bucur [16,22,33], using the ultrasonic method in the case of curly sycamore maple were: density $\rho = 0.700\ \mathrm{g/cm^3}$, the velocities $V_{LL} = 4350\ \mathrm{m/s}$; $V_{RR} = 2590\ \mathrm{m/s}$; $V_{TT} = 1914\ \mathrm{m/s}$; and for shear velocity $V_{LT} = 1468\ \mathrm{m/s}$; $V_{RT} = 812\ \mathrm{m/s}$; $V_{LR} = 1744\ \mathrm{m/s}$. For common Sycamore, the values were: $\rho = 0.623\ \mathrm{g/cm^3}$, the following longitudinal velocities $V_{LL} = 4695\ \mathrm{m/s}$; $V_{RR} = 2148\ \mathrm{m/s}$, $V_{TT} = 1878\ \mathrm{m/s}$; and for shear velocity $V_{LT} = 1148\ \mathrm{m/s}$; $V_{RT} = 630\ \mathrm{m/s}$; $V_{LR} = 1354\ \mathrm{m/s}$. For sycamore, Spycher et al. [13] obtained a density of $\rho = 0.625 \pm 0.022\ \mathrm{g/cm^3}$, sound velocity $V_{LL} = 3894 \pm 310\ \mathrm{m/s}$, $V_{RR} = 1662 \pm 97\ \mathrm{m/s}$, Young's modulus in the longitudinal direction, $E_L = 9.707 \pm 1.13$ GPa and in the radial direction, $E_R = 1.703 \pm 0.236$ GPa. For the control samples, the following values were obtained: $\rho = 0.569 \pm 0.015\ \mathrm{g/cm^3}$, $V_{LL} = 4180 \pm 143\ \mathrm{m/s}$, $V_{RR} = 1703 \pm 24\ \mathrm{m/s}$, $E_L = 9.974 \pm 0.769$ GPa and $E_R = 1.654 \pm 0.066$ GPa. Using the vibrational tests, based on non-contact forced–released vibrations of free-end bars, Bremaud [34] and Carlier et al. [35] reported sycamore with density of $\rho = 0.6\ \mathrm{g/cm^3}$, sound velocity in longitudinal direction of around $V_{LL} = 3660\ \mathrm{m/s}$ and $V_{RR} = 1560\ \mathrm{m/s}$. Cretu et al. [17] applied a hybrid method to determine the sound velocity in sycamore maple wood, obtaining $V_{LL} = 4341 \pm 296\ \mathrm{m/s}$ and $V_{RR} = 2001 \pm 58\ \mathrm{m/s}$.

3.4. Statistical Correlations between Physical and Acoustic/Elastic Features

Since the hypotheses of the study were focused on identifying the links between the appearance and pattern of sycamore maple wood and its acoustic and elastic properties, the experimental data were analyzed statistically, going through several stages of analysis, in terms of the methodology presented in Section 2.2.4. Thus, the discriminant analysis showed that only the wood density had the ability to separate the quality classes of the sycamore maple wood samples. The polarization of the density values according to the physical quality class of the sample can be traced in Figure 5a. It can be noted that there was regression of the size of the density in the first three quality classes. Quality class D samples showed the largest amplitudes of the density magnitude. Quality class A was the most homogeneous in terms of wood density. With the exception of Poisson's ratio υ_{RT}, sycamore maple wood was homogeneous in terms of acoustic properties (small coefficients of variation between samples) (Figure 5b). In Figure 5c, it can be seen that the stratification of the sound propagation speed in the longitudinal direction depended on the anatomical quality classes. With the exception of the propagation speed in the tangential direction V_{TT}, the Young's modulus in the radial direction E_R and the shear modulus G_{LT}, the acoustic variables involved in the study presented non-Gaussian distributions (Shapiro–wilk $W = 0.85 \div 0.98$, $p \leq 0.05$). For this reason, significance tests were adopted from the area of non-parametric statistics.

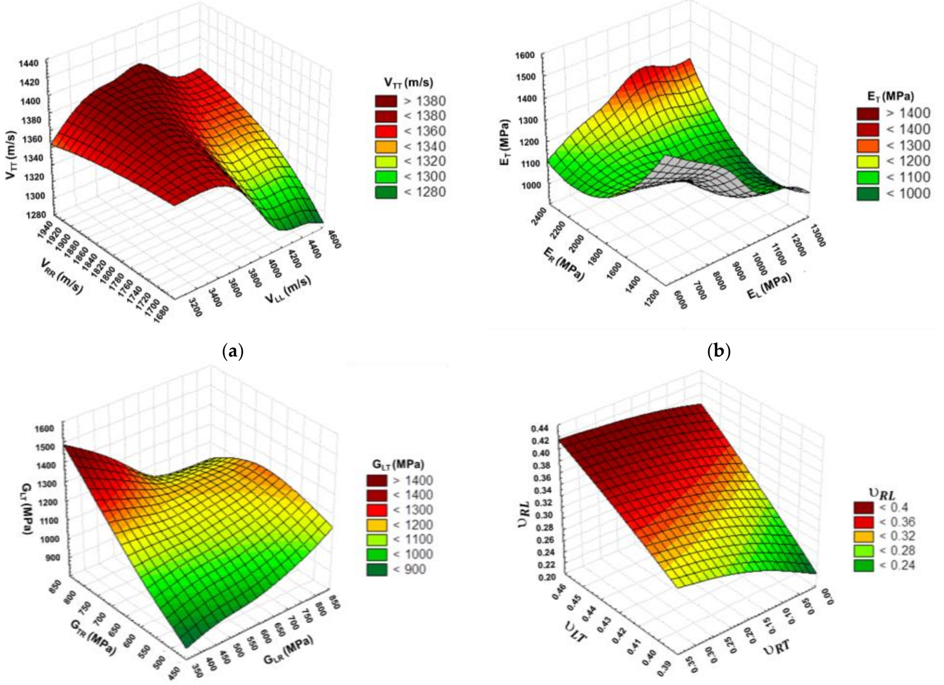
Statistical analysis revealed that the reciprocal links between the acoustic variables in the case of sycamore maple wood were of moderate to strong intensity; the exception was wood density and Poisson coefficient υ_{RT}. The size of the wood density was not an indicator for the size of the ultrasound propagation speeds in the three directions, nor for the shear moduli. The closest connection (Spearman correlation coefficient $R = +0.976$, $p < 0.0001$) was between the shear modulus G_{RT} and the sound propagation velocity in the radial direction V_{RR}. The relationships between the magnitudes of the ultrasound velocity, the Young's moduli and the Poisson coefficients in the three directions were of moderate intensity. Instead, the links between shear moduli G sizes were tighter, as can be seen in the multiple correlations between the acoustic and elastic parameters determined for the sycamore maple wood samples (Figure 6).



(a) (b)

(c)

Figure 5. The stratification of sycamore maple wood, according to the specimen grade, in the case of: (**a**) density; (**b**) Poisson coefficient υ_{RL}; (**c**) sound velocity in longitudinal direction V_{LL}.



(a) (b)

(c) (d)

Figure 6. Multiple correlations between some acoustic and elastic parameters determined for the sycamore maple wood samples: (**a**) ultrasound velocity in L, R, and T directions; (**b**) longitudinal elasticity moduli in L, R, and T directions; (**c**) shear moduli G; (**d**) Poisson coefficients.

Using factor analysis, four principal components were extracted, with the first two together explaining 75% of the total variance. The first principal component was defined by the Poisson's ratio υ_{RT} and the quality class of the sample, which varied in contrast with the width of the annual rings and the wood density (Figure 7). The second component was defined by the sound speed in the radial direction V_{RR} and the shear modules G oriented in the RT and LR planes. At the opposite extreme were the longitudinal propagation velocity V_{LL} and Poisson's ratios in the longitudinal direction. So, the anisotropy axes, L and R, were divergent in the magnitude of the physical–acoustic indices. The degree of yellowness (b*) had no relevance in relation to the physical–acoustic properties of the wood. Instead, the brightness varied with the shear moduli G and the radial velocity. The redness (a*) varied in tandem with the modulus of elasticity, velocity of ultrasound propagation and transverse contraction coefficients. The regularity of the annual rings did not seem to influence the acoustic variables, instead the width of the annual rings was closely related to the wood density, as can be seen in Figure 7. Thus, the PCA (Figure 7) highlighted the association tendency of the variables, which was also verified with the k-means clustering analysis. This identified three groups, which separated the Young's modulus E_L from the sound velocity in wood, the Young's moduli E_R and E_T moduli, as well as the shear moduli. The third group would consist of physical indices (quality class, wood structure, wood color, density). So, the physical characteristics dissociated from the acoustic parameters, except for the shear moduli G_{TR} and G_{LR}.

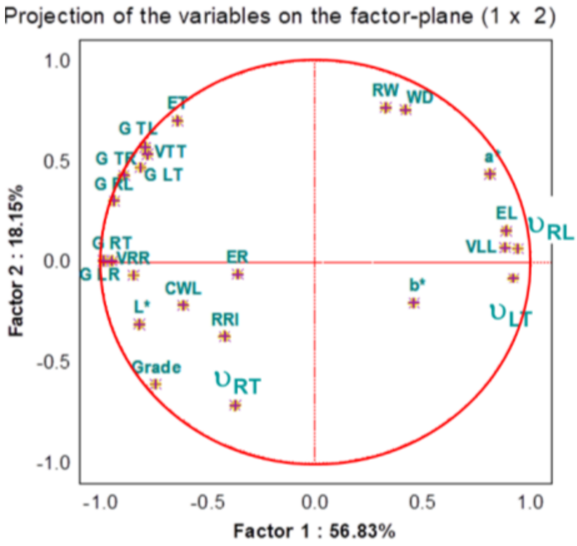


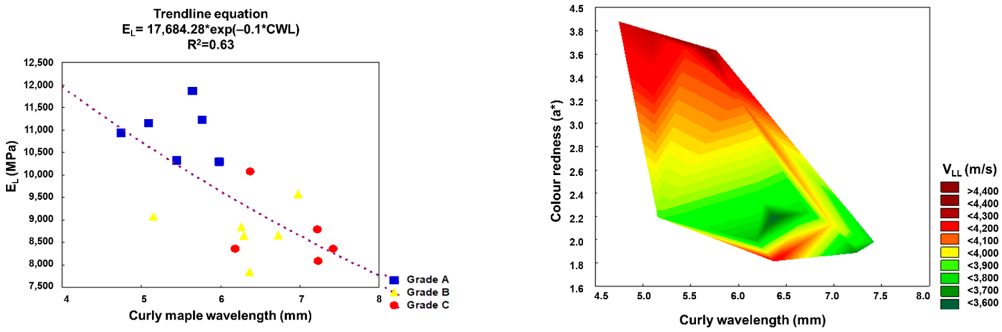
Figure 7. The physical, acoustic, and elastic parameters in the 1,2 planes of the PCA. Legend: Grade, the quality class of sycamore maple wood; CWL, the fiber undulation pitch; RRI, the ring width regularity index; RW, the annual ring width; b*, color yellowness; a*, redness color; L*, brightness color; WD, wood density; EL, Young's modulus along the wood fibers; υ_{RT} and υ_{LT} Poisson coefficients; V_{LL}, sound velocity in the longitudinal direction of the wood (along the grain); G_{LT} and G_{LR}, shear moduli; V_{TT}, sound velocity in the tangential direction of wood; E_R, Young's modulus in the radial direction of wood.

In Table 4 it can be noted that the variables of the annual rings (width and regularity) were independent of the size of the other variables involved in the study; in particular, the geometry of the rings had nothing to do with the G values in different directions. A certain indication could provide the regularity of the rings in relation to the size of the modulus of elasticity in the radial direction. Thus, sycamore maple wood with rings of relatively constant width presented low values of the modulus of elasticity in the radial direction. Instead, the pitch of the curly fiber (CWL) correlated with the size of the wood density, the shear moduli, the Poisson's coefficients and, especially, the elasticity modulus in the longitudinal direction E_L. The connection can be observed in Figure 7a. The fiber pitch had an unexpectedly large contribution of 63% to variations in the size of elasticity modulus in the longitudinal direction E_L (Figure 7a). Dense-grained sycamore maple wood (i.e., with a small wave pitch) was heavier, conducts ultrasound more easily along the grain, has better elasticity, higher transverse coefficients, and lower shear moduli. The L* and a* components of the color were relevant to the size of the density, the velocities of propagation along the directions, the Poisson coefficients and some shear moduli, as can be seen in Table 4. It can be seen from the bold values, which were significant for $p < 0.05$, in Table 4, that the following elastic and acoustic sizes E_L, υ_{RL}, V_{LL}, G_{LR} and G_{TL} were the properties best described by the physical properties of the wood (in fact, by the CWL and a*).

Table 4. Matrix of simple Spearman correlation coefficients between acoustic parameters and physical characteristics of the sycamore maple wood (Legend: Values marked in bold are significant for $p < 0.05$).

Variables	Coefficients of Simple Correlation *					
	WL	**RRI**	**CWL**	**L***	**a***	**b***
WD	0.1905	−0.0534	**−0.6388**	**−0.6096**	**0.6470**	0.1191
V_{LL}	0.2483	−0.0932	**−0.7089**	**−0.4165**	**0.5678**	0.2826
V_{RR}	−0.1378	0.3714	0.3828	**0.5173**	**−0.4791**	−0.3765
V_{TT}	0.1013	0.1172	0.2776	0.2269	−0.1773	−0.2739
E_L	0.2400	−0.1007	**−0.7481**	**−0.5295**	**0.6600**	0.3086
E_R	−0.1691	**0.4390**	0.1248	0.1008	−0.1408	−0.1260
E_T	0.0713	0.0766	0.1207	−0.0408	0.0826	−0.2400
υ_{LT}	0.1272	−0.0940	**−0.6256**	−0.3166	**0.4372**	0.2909
υ_{RL}	0.2579	−0.3039	**−0.6752**	**−0.5097**	**0.6024**	0.3553
υ_{RT}	−0.2487	0.3458	0.1104	0.3443	−0.3052	−0.1295
G_{LT}	0.0243	0.3249	0.2591	0.2296	−0.1809	−0.3144
G_{RL}	−0.0487	0.2917	**0.4840**	0.2913	−0.2869	−0.3634
G_{RT}	−0.1461	0.3729	0.4468	**0.5382**	**−0.5182**	−0.3834
G_{TL}	−0.0082	−0.0165	**0.5748**	0.1165	−0.1556	−0.2643
G_{TR}	−0.0247	0.2083	**0.5624**	0.1409	−0.1869	−0.3992
G_{LR}	−0.2279	0.2655	**0.6264**	**0.4540**	**−0.5166**	**−0.4574**

Multiple regression allowed the development of predictive models with high explanatory capacity ($R^2 > 0.5$) (Figure 8a). These predictive models, presented in Table 5, allowed estimation of the size of some acoustic and elastic properties, depending on the size of some physical and anatomical characteristics, such as the pitch of the wavy fiber and the yellow color of the sycamore maple wood. A similar method was used by [36] for predictive models in the case of spruce wood. Both the experimental data (Figure 8b) and the model fitted to them (Table 5) showed that, in the case of sycamore wood used for the construction of musical instruments, the magnitude of the velocity of sound propagation along the fiber, for example, decreased with increasing the wave pitch of the fiber.



(**a**) (**b**)

Figure 8. Correlations between physical, anatomical and elastic parameters of sycamore maple wood: (**a**) regression of modulus of elasticity in longitudinal direction with curly fiber pitch; (**b**) prediction of the multiple correlations between the anatomical, physical and elastic characteristics of maple wood.

Table 5. Wood physical traits as predictors of some wood acoustics and elastic properties.

Dependent Variable	Predictors	Statistical Model	Adjusted R^2	F	p
E_L	CWL, a*	$E_L = 6342.12 - 42.87CWL + 1319.69a^*$	0.7	20.06	<0.001
υ_{RL}		$\upsilon_{RL} = 0.256 + 0.002CWL + 0.034a^*$	0.6	12.9	<0.001
V_{LL}		$V_{LL} = 3467.26 - 17.74CWL + 234.71a^*$	0.6	12.95	<0.002

4. Conclusions

The presented study provides both a valuable database regarding the physical and acoustic characteristics of sycamore maple wood from the forests of Romania, as well as the existing statistical correlations between the different measured parameters. Moreover, the application of multiple regression allowed the development of predictive models with high explanatory capacity that allow estimation of the size of some acoustic and elastic properties, depending on the size of some physical and anatomical factors, known or easily determined. The main findings were as follows:

- the link between the values of the physical parameters and the acoustic and elastic properties of sycamore maple wood was confirmed, according to the quality classes used by luthiers for musical instruments;
- the Spearman rank-order correlation coefficient between the wavelength and the width of the rings was −0.367 (*p* = 0.13) and the correlation between the wavelength and the regularity of the rings was −0.075 (*p* = 0.79). From here it followed that there was no connection between the geometry of the rings and the curly grain. Therefore, the degree of curly grain can only be justified with the wavelength (if the wavelength is small, which means a pronounced undulation, and if the wavelength is large, it means a low degree of curly grain);
- wood density is the variable that best separates the quality classes of sycamore maple wood samples;
- acoustic properties (sound propagation speed) are not influenced by color parameter, but the redness correlates with elastic properties;
- the closest correlation was observed between the shear modulus G_{RT} and the sound propagation speed in the radial direction V_{RR};
- the anisotropy axes, L and R, are divergent in the size of the physical and acoustic features;
- the pitch of the wavy fiber has a contribution of 63% to the magnitude variations of the longitudinal modulus of elasticity (E_L).

In future studies, quantitative and qualitative analyses of the anatomical elements of sycamore maple wood will be considered according to the quality classes.

Author Contributions: Conceptualization, M.D.S., F.D. and A.S.; methodology, F.D. and A.S.; software, F.D., M.D.S. and A.S.; validation, F.D. and M.D.S.; formal analysis, F.D.; investigation, F.D. and A.S.; resources, M.D.S. and A.S.; data curation, M.D.S.; writing—original draft preparation, M.D.S.; writing—review and editing, F.D. and A.S.; visualization, M.D.S. and F.D.; supervision, A.S. and F.D.; project administration, M.D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a grant from the Ministry of Research, Innovation and Digitization, CNCS/CCCDI—UEFISCDI, project number 61PCE/2022, PN-III-P4-PCE2021-0885, ACADIA—Qualitative, dynamic and acoustic analysis of anisotropic systems with modified interfaces.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to the technical staff of Gliga Musical Instruments, Reghin, a Romanian manufacturer of musical string instruments, for supplying the specimens.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nagyvary, J.; DiVerdi, J.; Owen, N.; Tolley, H.D. Wood used by Stradivari and Guarneri. *Nature* **2006**, *444*, 565. [CrossRef] [PubMed]
2. Tai, H.C.; Li, G.C.; Huang, S.J.; Jhu, C.-R.; Chung, J.-H.; Wang, B.Y.; Hsu, C.-S.; Brandmair, B.; Chung, D.-T.; Chen, H.M. Chemical distinctions between Stradivari's maple and modern tonewood. *Proc. Natl. Acad. Sci. USA* **2016**, *114*, 27–32. [CrossRef] [PubMed]
3. Stanciu, M.D.; Mihălcică, M.; Dinulică, F.; Nauncef, A.M.; Purdoiu, R.; Lăcătuș, R.; Gliga, G.V. X-ray Imaging and Computed Tomography for the Identification of Geometry and Construction Elements in the Structure of Old Violins. *Materials* **2021**, *14*, 5926. [CrossRef]
4. Sedlar, T.; Šefc, B.; Stojnić, S.; Sinković, T. Wood quality characterization of sycamore maple (*Acer pseudoplatanus* L.) and its utilization in wood products industries. *Croat. J. Eng.* **2021**, *42*, 543–560. [CrossRef]
5. Sonderegger, W.; Martienssen, A.; Nitsche, C.; Ozyhar, T.; Kaliske, M.; Niemz, P. Investigations on the physical and mechanical behavior of sycamore maple (*Acer pseudoplatanus* L.). *Eur. J. Wood Prod.* **2013**, *71*, 91–99. [CrossRef]
6. Krajnc, L.; Čufar, K.; Brus, R. Characteristics and geographical distribution of fiddleback figure in wood of Acer pseudoplatanus L in Slovenia. *Drv. Ind.* **2015**, *66*, 213–220. [CrossRef]
7. Quambusch, M.; Bäucker, C.; Haag, V.; Meier-Dinkel, A. Growth performance and wood structure of wavy grain sycamore maple (*Acer pseudoplatanus* L.) in a progeny trial. *Ann. For. Sci.* **2021**, *78*, 15. [CrossRef]
8. Beals, H.; Davis, T. *Figure in Wood—An Illustrated Review*; Agricultural Experiment Station, Auburn University: Auburn, AL, USA, 1977. Available online: https://aurora.auburn.edu/handle/11200/2414 (accessed on 6 November 2022).
9. Harris, J.M. *Spiral Grain and Wave Phenomena in Wood Formation*; Springer: New York, NY, USA, 1989.
10. Savidge, R.A.; Farrar, J.L. Cellular adjustments in the vascular cambium leading to spiral grain formation in conifers. *Can. J. Bot.* **1984**, *62*, 2872–2879. [CrossRef]
11. Binggeli, P. Invasive Woody Plants. 1999. Available online: https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.2884#REF-DDB--25 (accessed on 30 December 2022).
12. Kollmann, F.F.P.; Côté, W.A., Jr. Principles of Wood Science and Technology, vol I. In *Solid Wood*; Springer: Berlin/Heidelberg, Germany, 1968.
13. Spycher, M.; Schwarze, F.W.M.R.; Steiger, R. Assessment of resonance wood quality by comparing its physical and histological properties. *Wood Sci. Technol.* **2008**, *42*, 325–342. [CrossRef]
14. Alkadri, A.; Carlier, C.; Wahyundi, I.; Grill, J.; Langbour, P.; Bremaud, I. Relationships between anatomical and vibrational properties of wavy sycamore. *IAWA—Intern. Assoc. Wood Anat. J.* **2018**, *39*, 63–86. Available online: https://hal.archives-ouvertes.fr/hal-01667816 (accessed on 6 November 2022). [CrossRef]
15. Stanciu, M.D.; Coşereanu, C.; Dinulică, F.; Bucur, V. Effect of wood species on vibration modes of violins plates. *Eur. J. Wood Prod.* **2020**, *78*, 785–799. [CrossRef]
16. Bucur, V. Wood species for musical instruments. In *Handbook of Materials for String Musical Instruments*; Springer: Cham, Switzerland, 2016; pp. 283–320. [CrossRef]
17. Crețu, N.; Roșca, I.C.; Stanciu, M.D.; Gliga, V.G.; Cerbu, C. Evaluation of wave velocity in orthotropic media based on intrinsic transfer matrix. *Exp. Mech.* **2022**, *62*, 1595–1602. [CrossRef]
18. Kudela, J.; Kunštar, M. Physical-acoustical characteristics of maple wood with wavy structure. *Ann. Wars. Univ. Life Sci.* **2011**, *75*, 12–18.
19. Yoshikawa, S. Acoustical classification of woods for string instruments. *J. Acoust. Soc. Am.* **2007**, *122*, 568–573. [CrossRef]
20. Stanciu, M.D.; Curtu, I.; Moisan, E.; Man, D.; Savin, A.; Dobrescu, G. Rheological Behaviour of Curly Maple Wood (Acer Pseudoplatanus) Used for Back Side of Violin. *ProLigno* **2015**, *11*, 73–80.
21. Gliga, V.G.; Stanciu, M.D.; Nastac, S.M.; Campean, M. Modal Analysis of Violin Bodies with Back Plates Made of Different Wood Species. *BioResources* **2020**, *15*, 7687–7713. [CrossRef]
22. Bucur, V.; Archer, R.R. Elastic constants for wood by an ultrasonic method. *Wood Sci. Technol.* **1984**, *18*, 255–265. [CrossRef]
23. Fedyukov, V.; Saldaeva, E.; Chernova, M. Different ways of elastic modulus comparative study to predict resonant properties of standing spruce wood. *Wood Res.* **2017**, *62*, 607–614.
24. Dinulică, F.; Stanciu, M.D.; Savin, A. Correlation between Anatomical Grading and Acoustic–Elastic Properties of Resonant SpruceWood Used for Musical Instruments. *Forests* **2021**, *12*, 1122. [CrossRef]
25. Viala, R.; Placet, V.; Cogan, S. Simultaneous non-destructive identification of multiple elastic and damping properties of spruce tonewood to improve grading. *J. Cult. Herit.* **2020**, *42*, 108–116. [CrossRef]
26. Gonçalves, R.; Trinca, A.J. Comparison of elastic constants of wood determined by ultrasonic wave propagation and static compression testing. *Wood Fiber Sci.* **2011**, *43*, 64–75.
27. Fang, Y.; Lin, L.; Feng, H.; Lu, Z.; Emms, G.W. Review of the use of air-coupled ultrasonic technologies for nondestructive testing of wood and wood products. *Comput. Electron. Agric.* **2017**, *137*, 79–87. [CrossRef]

28. Rocaboy, F.; Bucur, V. About the physical properties of wood of twentieth century violins. *J. Acoust. Soc. Am.* **1990**, *1*, 21–28.
29. Dinulica, F.; Albu, C.; Borz, A.S.; Vasilescu, M.M.; Petrițan, C. Specific structural indexes for resonance Norway spruce wood used for violin manufacturing. *Bioresources* **2015**, *10*, 7525–7543. [CrossRef]
30. Pilcher, J.R. Sample preparation, cross-dating and measurement. In *Methods of Dendrochronology*; Cook, E.R., Kairiukstis, L.A., Eds.; Kluwer Academis Publishing: Dordrecht, The Netherlands, 1990; pp. 40–51.
31. Zar, J.H. *Biostatistical Analysis*; Prentice-Hall Inc.: Englewood Cliffs, NJ, USA, 1974.
32. Carlson, D. MANOVA and Discriminant Analysis. In *Quantitative Methods in Archaeology Using R*; Cambridge Manuals in Archaeology; Cambridge University Press: Cambridge, UK, 2017; pp. 244–264. [CrossRef]
33. Bucur, V. Varieties of resonance wood and their elastic constants. *J. Catgut Acoust. Soc.* **1987**, *47*, 42–48.
34. Brémaud, I. Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity. *J. Acoust. Soc. Am.* **2012**, *131*, 807–818. [CrossRef]
35. Carlier, C.; Brémaud, I.; Gril, J. Violin making "tonewood": Comparing makers' empirical expertise with wood structural/visual and acoustical properties. In Proceedings of the International Symposium on Musical Acoustics ISMA2014, Le Mans, France, 7–12 July 2014; pp. 325–330.
36. Dinulică, F.; Bucur, V.; Albu, C.T.; Vasilescu, M.M.; Curtu, A.L.; Nicolescu, N.V. Relevant phenotypic descriptors of the resonance Norway spruce standing trees for the acoustical quality of wood for musical instruments. *Eur. J. Forest Res.* **2021**, *140*, 105–125. [CrossRef]