Correlation between Anatomical Grading and Acoustic–Elastic Properties of Resonant Spruce Wood Used for Musical Instruments

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Abstract: This paper deals with the acoustic and elastic properties of resonant wood, classified into four classes, according to the classification of wood quality by the manufacturers of musical instruments. Traditionally, the quality grades of resonant wood are determined on the basis of the visual inspections of the macroscopic characteristics of the wood (annual ring width, regularity, proportion of early and late wood, absence of defects, etc.). Therefore, in this research, we studied whether there are correlations between the acoustic and elastic properties and the anatomical characteristics of wood used for the construction of violins. The results regarding the identification of the anatomical properties of resonant spruce, the wood color, and the acoustic/elastic properties, determined by ultrasonic measurements, were statistically analyzed to highlight the connection between the determined properties. From the statistical analysis, it can be seen that the only variables with the power to separate the quality classes are (in descending order of importance) the speed of sound propagation in the radial direction, Poisson’s ratio in the longitudinal–radial direction, and the speed of propagation of sounds in the longitudinal direction.

Keywords: anatomical patterns; resonant spruce; acoustic properties; elastic properties; Discriminant Function Analysis; Principal Components Analysis

1. Introduction

Numerous studies concerning the acoustical behavior of violins refer to the similarities and differences in the tonal qualities, produced by good and bad, and old and new instruments, depending on various factors [1–4]. Wood with anatomical and acoustic properties used in the construction of stringed musical instruments is also known as resonant wood, tonewood, or music wood. The acoustical characteristics of wood species are criteria for the selection of the most appropriate raw material for making violins [4–6]. The behavior of wood in the acoustic field is conditioned by its elastic properties, which are characterized by the longitudinal modulus of elasticity, the shear modulus, and Poisson’s ratio, according to the three planes of the anisotropy of wood (longitudinal, radial, tangential). The size of these constants is critical in the selection of resonant wood. Numerous studies have shown the existence of close correlations between the physical properties of the resonant wood structure and the elastic ones [7–9].

In the past, luthiers did not have the knowledge and techniques necessary for determining the acoustic and elastic properties of wood as they do today, with the recognition of resonant wood being based on the macroscopic analysis of the structure of softwood. Thus, the need for the material to have narrow and regular rings was established; the contribution...
of a few late wood to this is modest [10–13]. The relevance of the annual ring structure as an acoustic marker remains debatable. Some have opined that the vibrational properties of wood are determined on the scale of the cell wall rather than on the macroscopic scale of the growth rings [12–14]. In the stringed instruments industry, musical instruments are classified according to the anatomical quality of the wood used in their construction, with this aspect being revealed in the final price of the instrument [15–17]. The classification of quality raw materials for the manufacture of stringed instruments is discussed in detail elsewhere [16–18]. Resonant wood is divided into four quality grades: A, high anatomical quality; B, average quality; C, low anatomical quality; D, common wood, without defects. The main anatomical parameters of resonant wood are the total ring width, the proportion of late wood within the annual ring, the width difference between two consecutive growth rings, and the regularity of the ring widths. The longitudinal and transverse propagation speeds in the wood, in the three directions, and the elastic characteristics, complete the icon of resonant wood [18–20]. Knowing this, as well as the density of the wood, one can estimate a number of acoustic parameters of resonant wood [17–21]. Wegst, 2006, noted that the Young and shear moduli parallel and perpendicular to the wood fibers are important parameters for musical plate vibration in the structure of chordophone instruments [20]. Therefore, the static and dynamic moduli of tonewood related to anatomical parameters influence the acoustic quality of wood. The vibration of flat orthotropic plates, such as violin plates, involves the flexural plate modes, which are two-dimensional, while the frequency depends on several elastic parameters of anisotropic media, as noted by [21–23]. In regard to the orthotropic anisotropy of wood, the following ratios should be taken into consideration: the ratio of Young’s moduli $E_L/E_R$, the ratio of shear moduli $E_L/E_T$, the ratio of shear moduli $G_{LR}/G_{RT}$, and Poisson’s ratios [20–24], where L, R, and T are the main directions in wood (L, longitudinal (along fibers); R, radial; and T, tangential) and LR, RT, and LT are the planes formed according to the main directions, as can be seen in Figure 1b. In addition to the values for the elastic and physical properties, research has shown that the value of the specific modulus in the radial direction ($E_R/\rho$; $G_{LR}/\rho$) [25].

![Figure 1](image_url)
In previous research, the propagation of waves in isotropic and anisotropic materials and the determination of the elastic properties of wood have been widely discussed. However, the data concerning the resonant spruce in the Carpathian Mountains is poor, although some of the largest factories in southeastern Europe in terms of the production of stringed instruments are located in Romania. The novelty of the study lies in its analysis of the sensitivity of the acoustic and elastic properties of wood according to the anatomical classification of the resonant wood harvested from the Carpathian Mountains, unlike other studies that have targeted resonant wood from other forest basins without making rigorous distinctions between the anatomical quality classes used by manufacturers. The statistical correlations between the anatomical features of wood and the elastic and acoustic properties of spruce provide rich information about the weights of predictive variables, the group membership, and if the groups differ with regard to the mean of a variable. Unlike the data from the literature, in this study, the acoustic and elastic properties of spruce wood were determined for all three main directions, meaning that a complete characterization of the resonant wood can be made from an elastic and acoustic point of view.

The aim of this paper was to identify the acoustic properties of the material that best depict the quality classes defined by anatomical criteria within the resonant spruce. For this purpose, the structure of the annual rings was introduced in digital format and statistically correlated with the following acoustic parameters determined by ultrasonic means: sound velocity in resonant spruce, Young’s moduli, shear moduli, and Poisson coefficients.

2. Materials and Methods
2.1. Materials

The samples of Norway spruce (Picea abies L. Karst.), 40 mm in size and oriented towards the symmetry planes, were delivered by Gliga Musical Instruments, Reghin, Romania (https://gliga.ro/ (accessed on 20 January 2021)). The samples were cut from the same batch of tonewood raw material from which the violin boards were cut. The raw material had been sorted since the primary cutting of the spruce logs according to the quality class of the violins, taking into account the anatomical characteristics of the spruce wood (Figure 1a). Before entering the violin manufacturing flow, the wooden parts were dried naturally for at least 3 years (for school violins) and up to 10 years for maestro violins. From the stage of the radial cutting of the logs, the semi-finished products were selected according to their quality class, paired for future violin boards, and stored for natural drying [11–14]. To measure the acoustic properties in the three main directions of the wood, the samples were accurately cut perpendicular to the principal direction (longitudinal L, radial R, tangential T) along which the ultrasonic waves propagate (Figure 1b). This is a mandatory requirement when determining acoustic parameters using the ultrasound method. Being extracted from the semi-finished products prepared for the entry on the technological flow of the violins, the moisture content of the wood was checked and found to be around 6–8%. Being a high quality wood and carefully selected from the primary processing phase, the number of samples analyzed was relatively small compared to the number of samples used for other determinations. The physical characteristics of the resonant spruce samples are portrayed in Table 1.
The sizes (mm) 

| Physical Features | A   | STDV | B   | STDV | C   | STDV | D   | STDV |
|-------------------|-----|------|-----|------|-----|------|-----|------|
| Longitudinal      | 40.508 | 0.187 | 40.304 | 0.706 | 40.116 | 0.120 | 39.957 | 0.157 |
| Radial            | 40.326 | 0.137 | 40.291 | 0.159 | 40.136 | 0.099 | 40.259 | 0.112 |
| Tangential        | 40.324 | 0.110 | 40.020 | 0.091 | 40.126 | 0.135 | 40.146 | 0.116 |
| Mass (g)          | 28.85  | 1.817 | 24.760 | 0.554 | 28.831 | 1.359 | 25.44  | 0.635 |
| Density $\rho$ (kg/m$^3$) | 438  | 2.035 | 381  | 4.291 | 446  | 8.695 | 394  | 3.663 |
| No. of annual rings/sample | 56  | 0.158 | 29  | 0.223 | 23  | 0.374 | 14  | 0.347 |

2.2. Methods

2.2.1. Wood Anatomical Data Acquisition

The tree ring data were gathered using the WinDENDRO Density image analysis system (Régent Instruments Inc., Québec City, QC, Canada, 2007) from the Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Transilvania University of Brașov, Romania. The samples were scanned at a resolution of 2200 dpi. The width of the annual rings was measured digitally in the cross section of the spruce samples. The measurements were performed with an accuracy of 0.001 mm. The early wood (EW) and late wood (LW) demarcation was obtained by tracing a straight path interactively (Figure 2). The database, originally in.txt format, was imported/converted and primarily processed in Microsoft Excel. The digital format of the growth rings consists of the total ring width (TRW), the early wood width (EWW), the late wood width (LWW), the early wood proportion (EWP), and the late wood proportion (LWP) from TRW [16–20]. Regarding the anatomical features of spruce wood—it is known that this species is characterized by distinct areas of early wood formed in the vegetative period and late wood, formed in the period of vegetative rest, being composed of tracheid, rays, and resin channels. Early wood areas are characterized by a low density due to well-developed wood cells, whereas late wood areas have a higher density due to the period of vegetative dormancy and high lignin content [26–28]. The small width of the annual rings, their regularity, and the proportions of early wood and late wood are the characteristics based on which wood for use in musical instruments is selected [29].

![Figure 2. The demarcation boundary between early wood and late wood performed with the WinDENDRO density image analysis system.](image_url)

The raw data were stacked into chronological series, where each ring was identified by the calendar year ($i$) in which it was formed. Using these raw variables, two more indices were produced for identifying the resonant wood: the difference in width between the consecutive rings DBR (mm) and the ring widths regularity index RI [16,17,24]. The DBR was calculated based on Formula (1) and the RI was calculated with Formula (2).

$$DBR = |TRW_{i+1} - TRW_i|,$$

(1)
\[ RI = \frac{\max(TRW_i) - \min(TRW_i)}{\max(TRW_i)}, \quad i = 1 \ldots n, \]  

where \( n \) is the number of rings that make up the time series.

Out of the different ways of expressing the regularity of the annual rings [11–13], the calculation method that best reflected the anatomic quality of the resonant wood was chosen. This method renders regularity as a ratio between the amplitude of variation (maximum value–minimum value) and the maximum value, a method of expression that is also used by [16].

2.2.2. Color Measurements of Wood Samples

The purpose of the wood color measurements was to check for correlations between wood color and acoustic/elastic properties for each resonant wood quality class. The color measurements were performed on longitudinal radial sections of samples, due to the utilization in violin plates. It is known that the wood color is affected by the physical features, as the angle of the light falling on the fibers and surface roughness [16–20]. In this sense, due to the wood grading for the manufacture of musical instruments, in A, B, C, and D groups, the color measurements of wood, in terms of the color brightness or whiteness (\( L^* \), %), the color redness/greenness (\( a^* \)) and the color yellowness/blueness (\( b^* \)) were performed using the Chroma Meter CR-400 (Konica Minolta, Tokyo, Japan) device [16,24,25].

2.2.3. Ultrasound Screening of Resonant Spruce Samples

Basically, ultrasound (US) nondestructive evaluation consists of applying physical elastic waves to the sample tested (1) and analyzing the interaction between the material samples and the field [26,29,30] (Figure 3a). To increase the reliability and assure the quality of the measurement, ultrafine force presses the US sensors (2) with a constant value. The two buffer rods of US sensors used in emission and reception are both identical, (2a, 2b) being made of the 7075-T6 aluminum–magnesium alloy with the density of \( 2.7 \times 10^3 \) kg/m\(^3\), the Young’s modulus of \( 7 \times 10^10 \) N/m\(^2\), the Poisson coefficient of 0.34, and a point curvature radius of 2 mm. The US sensors were connected to a 5073 PR Pulse Receiver–Panametrics equipment (3, 4). The visualization of the signal and the measurement of the time of propagation were carried out with the LeCroy Wave Runner 64Xi digital oscilloscope (5) with a sampling frequency of 10 G S/s. The samples (1) were marked to identify the position of the US transducer center of the measurement points corresponding to two opposite faces (Figure 3) and to plot the map of the US velocity distribution on each pair of inspected faces [31–34]. Ultrasonic measurement was performed on an \( 8 \times 8 \) mm\(^2\) grid at the intersection points of the grid to include as many annual growth rings as possible in order to increase the accuracy of the determinations. The total sum of the measurement points for each section amounted to 10 measurements. No measurements were made in the areas outside the grid (towards the edge) so as not to introduce measurement errors. The tests were carried out on 6 samples from each quality class, resulting in a total of 24 specimens and a total of 720 ultrasound measurements (60 per each sections from each quality class). The measurements were performed at a temperature of 24 °C and a humidity of 65%.
The theoretical considerations of propagation wave in orthotropic solids as wood are based on generalized Hook’s law, which describes the proportionality between the stress tensor and the strain deformation tensor (see relation (3)) (Figure 3b).

\[ \sigma_{ij} = C_{ijkl} \varepsilon_{kl}, \]  

(3)

where \( [\sigma_{ij}] \) is the stress tensor acting in direction \( i \) with its normal in direction \( j \); \( [C_{ijkl}] \) is the elasticity tensor; \( [\varepsilon_{kl}] \) is the strain tensor of small deformation \([12,13,35]\). If the Kelvin–Christoffel tensor \( \Gamma \) is introduced, we can write the relation between the elasticity tensor \( C_{ijkl} \) and the propagation vectors of ultrasound waves as \( n_j, n_l \) \([12,13]\):

\[ \Gamma_{ik} = C_{ijkl} * n_j * n_l, \]  

(4)

and

\[ (\Gamma_{ik} - \delta_{ik} * \rho * v_{phase}^2)P_m = 0, \]  

(5)

where \( \delta_{ik} \) is Kronecker tensor (if \( i = k \), then \( \delta_{ik} = 1 \) and if \( i \neq k \), then \( \delta_{ik} = 0 \)); \( P_m \) is the component of the unit vector in the direction of displacement (polarization); \( \rho \) is the density; \( v_{phase}^2 \) is the phase velocity \([12,13]\). The eigenvalues and the eigenvectors of the Christoffel equation can be written as a cubic polynomial in phase velocity squared

(6) \([12,13]\):

\[
\begin{bmatrix}
\Gamma_{LL} - \rho V^2 & \Gamma_{LR} & \Gamma_{LT} \\
\Gamma_{RL} & \Gamma_{RR} - \rho V^2 & \Gamma_{RT} \\
\Gamma_{TL} & \Gamma_{TR} & \Gamma_{TT} - \rho V^2
\end{bmatrix}
\begin{bmatrix}
p_L \\
p_R \\
p_T
\end{bmatrix} = 0,
\]

(6)

For unique solutions, the condition of Equation (6) is \( |P_m| = 0 \), then we obtain (7):

\[
\begin{bmatrix}
\Gamma_{LL} - \rho V^2 & \Gamma_{LR} & \Gamma_{LT} \\
\Gamma_{RL} & \Gamma_{RR} - \rho V^2 & \Gamma_{RT} \\
\Gamma_{TL} & \Gamma_{TR} & \Gamma_{TT} - \rho V^2
\end{bmatrix}
= 0.
\]

(7)
If we assume that the wood is an orthotropic material, then for wave propagation along the symmetry axes \((L, R, T)\) Equation (7) becomes (8) \([12,13]\):

\[
\begin{bmatrix}
  \Gamma_{LL} - \rho V^2 \\
  \Gamma_{RR} - \rho V^2 \\
  \Gamma_{TT} - \rho V^2
\end{bmatrix} = 0.
\] (8)

For determining the wave propagation in the longitudinal and transversal directions as well as the quasi-longitudinal wave (QL) and the quasi-transversal wave (QT), the components of the elasticity tensor \(C_{ijkl}\) will be calculated based on relations (9)–(11) \([12,13]\):

\[
V_{LL}^2 \star \rho = C_{LL}, \quad V_{LR}^2 \star \rho = C_{LR}, \quad V_{LT}^2 \star \rho = C_{LT}, \quad V_{RR}^2 \star \rho = C_{RR}, \quad V_{RT}^2 \star \rho = C_{RT}, \quad V_{TT}^2 \star \rho = C_{TT}. \] (9)

\[
2\rho V_{QL,QT}^2 = (\Gamma_{LL} + \Gamma_{RR}) \pm \sqrt{(\Gamma_{LL} - \Gamma_{RR})^2 + 4\Gamma_{LR}^2},
\]

\[
2\rho V_{QL,QT}^2 = (\Gamma_{LL} + \Gamma_{TT}) \pm \sqrt{(\Gamma_{LL} - \Gamma_{TT})^2 + 4\Gamma_{LT}^2},
\] (10)

\[
2\rho V_{QL,QT}^2 = (\Gamma_{RR} + \Gamma_{TT}) \pm \sqrt{(\Gamma_{RR} - \Gamma_{TT})^2 + 4\Gamma_{RT}^2},
\]

\[
\rho V_{L}^2 = C_{LT}n_1^2 + C_{RT}n_2^2,
\]

\[
\rho V_{R}^2 = C_{LR}n_1^2 + C_{RT}n_2^2,
\]

\[
\rho V_{L}^2 = C_{LT}n_1^2 + C_{LR}n_2^2. \] (11)

Thus, based on the nine terms of the stiffness matrix \([C]\) and inverting the matrix to obtain the compliance terms, the elastic parameters (Young’s moduli and Poisson’s ratios) can be calculated. The experimental data based on above formulas were calculated using the MATLAB program.

2.2.4. Data Statistical Processing

All of the experimentally obtained data were first examined for variability. Thus, the statistical analysis of the data began with the investigation of the level of variability of the measured characteristics in order to verify the possibility of stratifying the raw data. In the next stage, we verified, using a specific test, the possibility of stratifying the data according to the independent variables involved in the study. The possibility of stratifying the size of the acoustic parameters according to the quality class of the sample was verified using Discriminant Function Analysis (DFA). DFA provides the weights of the predictive variables, giving the ability to distinguish between groups of dependent variables. The individual ability of the acoustic variables to discriminate the quality class is indicated by the size of the partial lambda parameter; the closer it is to 0, the higher the discriminant power is. The normality of the distributions was verified with the Shapiro–Wilk test. The relationships between the acoustic parameters were verified by testing the 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; then, we verified the result with simple and multiple correlations.

3. Results and Discussion

3.1. The Anatomical Pattern and Color of Resonant Spruce

The width of the annual rings, their regularity, and the proportion of early wood and late wood are the characteristics on which the selection of wood for musical instruments is based. In Table 2, the anatomical features of tonewood spruce of different grades are shown.
Table 2. The anatomical features of spruce wood studied samples (legend: the first value represents the average, and the value in parentheses represents the standard deviation).

| Variables                        | Grade |
|----------------------------------|-------|
| **Average Values/STDV**          |       |
| Annual rings widths (mm)         |       |
| A                                | 0.71 (0.005) |
| B                                | 1.38 (0.018) |
| C                                | 1.69 (0.045) |
| D                                | 2.28 (0.005) |
| Early wood width (mm)            |       |
| A                                | 0.54 (0.011) |
| B                                | 1.07 (0.029) |
| C                                | 1.33 (0.039) |
| D                                | 1.74 (0.029) |
| Late wood width (mm)             |       |
| A                                | 0.18 (0.013) |
| B                                | 0.30 (0.013) |
| C                                | 0.36 (0.022) |
| D                                | 0.54 (0.026) |
| Early wood proportion (%)        |       |
| A                                | 74.97 (1.519) |
| B                                | 78.53 (1.203) |
| C                                | 78.71 (0.895) |
| D                                | 76.36 (1.138) |
| Late wood proportion (%)         |       |
| A                                | 25.03 (1.519) |
| B                                | 21.47 (1.203) |
| C                                | 21.29 (0.895) |
| D                                | 23.64 (1.136) |
| Lightness L* (%)                 |       |
| A                                | 84.15 (0.349) |
| B                                | 83.57 (0.398) |
| C                                | 84.21 (0.700) |
| D                                | 83.65 (0.120) |
| Green-red scale a*               |       |
| A                                | 2.54 (0.093) |
| B                                | 2.97 (0.149) |
| C                                | 2.47 (0.202) |
| D                                | 2.76 (0.093) |
| Blue-yellow b*                   |       |
| A                                | 19.78 (0.573) |
| B                                | 19.62 (0.163) |
| C                                | 20.02 (0.727) |
| D                                | 20.85 (0.223) |

All tree ring variables had a high degree of scattering (coefficients of variation 49–54%), which would allow their stratification. The proportion of early wood is the characteristic of the most stable annual rings from one sample to another. (Table 3).

Table 3. Descriptive statistics of the configuration of annual rings in the studied samples.

| Type of Variables | Symbol | Average Value | Coefficient of Variation (%) | The Chi-Square Test |
|-------------------|--------|---------------|------------------------------|--------------------|
| Ring width (mm)   | TRW    | 1.27393       | 48.74623                     | p < 0.001          |
| Early wood width (mm) | EWW   | 0.98172       | 49.11365                     | p < 0.001          |
| Late wood width (mm) | LWW  | 0.29220       | 53.96329                     | p < 0.001          |
| Early wood proportion (%) | EWP | 76.67656 | 7.31074 | p = 0.003 |
| Late wood proportion (%) | LWP | 23.32344 | 24.03427 | p = 0.004 |

The late wood width of spruce (with a median of 0.25 mm) is at the limit of the eyepieces. Since none of the annual ring variables conforms to a Gaussian distribution (W in the Shapiro–Wilk test = 0.898–0.967, p < 0.0001), we followed this with a nonparametric statistical analysis. The differences between the samples are statistically assured with regard to the size of the characteristics of the annual rings (Figure 4).

It is assumed that there is a control factor over the size of these characteristics that can allow the grouping of the samples into grades. Based on the Kruskal–Wallis H test, it was found that all the annual ring variables could be stratified according to the quality class of the material. The experimental data suggest a trend of decreasing the LWP related to the TRW of spruce, which, although statistically significant, is still not sufficiently consistent ($R^2 = 2.6\%$). This relationship was pursued at the level of quality classes A, B, C, and D, which were established by the manufacturers of musical instruments. It turned out that the inverse proportionality relationship is manifested only in quality class A; meanwhile, especially in quality class B, this relationship is positive (Table 4). It can be noticed that the analyzed samples are characterized by the same average values obtained by [4,5,11,12,16].

Table 4. Variation in the LWP according to the annual ring width stratified by the quality class of the sample (legend: significance p-level).

| Type of Stratification | Grade of Resonant Spruce Wood |
|------------------------|-------------------------------|
|                        | A    | B    | C    | D    |
| Rank-order correlation coefficients | $-0.327$ | 0.48 | 0.222 | 0.264 |
| p < 0.001 | p < 0.001 | p = 0.04 | p = 0.03 |
The correlations between the anatomical features and the qualitative classification of resonant spruce are shown in Figure 4. The tonewood density can also be stratified according to the quality class of the sample. The spruce wood from quality classes A and C is heavier by about 60 kg/m$^3$ than wood from classes B and D (Figure 5).

![Figure 4](image1.png)

**Figure 4.** Variation in the anatomical parameters according to the wood grade: (a) the early wood width EWT; (b) the late wood width LWT; (c) the early wood proportion EWP; (d) the late wood proportion LWP.

![Figure 5](image2.png)

**Figure 5.** The stratification of the density of spruce wood according to the specimen grade.
Despite the differences in the anatomical patterns of the annual rings of spruce, the color of the wood, especially the brightness (degree of white, $L^*$), had an unexpectedly low level of variability in the spruce samples examined. The distributions had different shapes from one color variable to another, with only the yellowness $b^*$ being distributed according to the normal law, as can be seen in Figure 6.

The differences between the samples are ensured statistically at a significant level. Brightness $L^*$ and redness $a^*$ are moderate significant, while yellowness $b^*$ is very significant, for fact for which the data were stratified according to the quality class. The brightness is a multimodal distributed and negatively skewed variable (Figure 6a). These modes suggest the color segregation in the examined samples. The redness is an exponentially decayed distributed variable; the mode is in the first class of values (2.3–2.5). Most values are concentrated towards the lower limit of the range of variation (Figure 6b). The size of the yellowness is a Gaussian variable, with the mode in the range of 19.4–19.9 (Figure 6c). In Figure 6d, the distribution of wood color according to quality class can be observed. Thus, the color of the spruce wood is distributed according to the quality class of the samples. However, the color differences between the quality classes are not so strong as to be perceptible by the human optical analyzer [16,18,25]. Spruce wood of A grade has a higher brightness than that of other grades and a lower degree of redness and yellowness. Additionally, for A wood grade, color variables have the smallest amplitudes of variation (Figure 6d). In the case of spruce wood from classes B and D, the content of redness is
higher; for class D, the highest content of wood that is yellow in color is observed. Wood grade C has the lowest redness content.

3.2. Acoustic and Elastic Parameters of Resonant Spruce

3.2.1. Discriminant Function Analysis (DFA)

In general, when studying the acoustic/vibrational properties of wood used in the construction of musical instruments, the most important quantities to be determined are the density, the speed of sound propagation in wood (most references report the values for the longitudinal propagation speed), and the module of longitudinal elasticity in the longitudinal and radial directions, as these quantities are the bases of the other acoustic quantities (acoustic radiation, acoustic impedance, acoustic radiation ratio, etc.). The results regarding the acoustic and elastic properties of tonewood are presented in Table 5. It can be noticed that the ratios of acoustic velocities (for A grade) are in good agreement with those found in other studies, such as [12–15,21–24,35–40]. For resonant spruce, Bucur, 2006 [15], obtained the ratios: $V_{LL}/V_{RR} = 2.8$, $V_{LL}/V_{TT} = 3.5$ and $V_{RR}/V_{TT} = 0.8$. From the experimental data, it can be noticed that a higher anisotropy was recorded for A and B grades. Related to the specific longitudinal modulus of elasticity, Carlier et al., 2014, 2018 [22,23], reported a wide range of density $\rho$ (0.32 to 0.55 g/cm$^3$), a specific modulus of elasticity in the longitudinal direction $E_L/\rho$ of 18 to 35 GPa, a longitudinal damping factor $\tan \delta_L$ of 0.006 to 0.100, a ring width $R_w$ of 0.77 to 2.52 mm, and a late wood percentage $L_w \%$ of 13 to 26%. This data is similar to those presented in Table 5. Additionally, there is a tendency to decrease the value of the specific module in relation to the decrease in the quality class with the increase in the width of the annual rings. In the radial direction, Viala et al., 2020 [21], found that the values of the specific elastic modulus vary between 1.46 and 2.78 GPa$^{-1}$ cm$^3$ compared to the values obtained in current study, which vary between 2.43 and 2.98 GPa$^{-1}$ cm$^3$ (Table 4). Additionally, in the longitudinal radial section the values of the specific shear modulus range from 1.86 to 2.51 GPa$^{-1}$ cm$^3$ and are very close to those reported by [21–23,36–40]. We note that these references used different methods to determine the elastic parameters in comparison with the authors of this study. Applying DFA—it was found that the resonant spruce wood is homogeneous in terms of density, the sound velocity in the wood, and the Poisson coefficient in the LT direction, which is reflected by the extremely small coefficients of variation (CV), as can be seen in Table 6. The elastic moduli ($E$ and $G$) show a moderate level of variability. The $\nu_{RT}$ coefficient recorded the highest value of variability. The dispersion degree of the average of the Young’s modulus values is higher in the tangential direction than either radially (R) or along the fiber (L), and it can be seen that the anisotropy is more accentuated in the RT section.

From the DFA, it can be seen (Table 6) that the only variables, out of the acoustic parameters, with the power to separate the quality classes are (in descending order of importance) the speed of sound propagation in the radial direction $V_{RR}$, Poisson’s ratio $\nu_{LR}$, and the speed of the propagation of sounds in the longitudinal direction $V_{LL}$. The longitudinal elasticity modulus $E_L$ (Table 6) also has a low contribution to the discrimination of quality classes. The other parameters are not stratified according to the grade of the samples. In the next stage, for the variables with the capacity to discriminate the quality classes (A, B, C, and D), the stratification according to their values in relation to these grades took place. The samples from class A show much more homogeneous elastic and acoustic characteristics than those from classes B, C, and D. Thus, the degree of spreading of the values of the measured parameters increases with the decrease in the quality class. With the exception of $G_{RT}$ and $\nu_{RT}$, the elastic and acoustic variables involved in this study have non-Gaussian distributions (Shapiro–Wilk $W = 0.84$–$0.91$, $p \leq 0.05$), which is why nonparametric statistics were chosen when testing the significance (Figure 7).
Table 5. The acoustic and elastic parameters.

| Type of Variables                  | Symbol | Grade of Resonant Spruce Wood Average Values |
|------------------------------------|--------|-----------------------------------------------|
|                                    |        | A    | B    | C    | D    |
| Density (kg/m³)                    | ρ      | 438  | 381  | 446  | 394  |
|                                    | STDV   | 2.035| 4.291| 8.695| 3.663|
| Sound velocity in wood (m/s)       | VLL    | 5005.74| 4856.55| 4688.94| 4283.40|
|                                    | VRR    | 1703.27| 1594.62| 1660.39| 1687.40|
|                                    | VTT    | 1374.57| 1227.63| 1296.72| 1409.18|
| Young’s elasticity modulus (MPa)   | E_L    | 102.505.84| 9421.53| 9595.21| 7011.00|
|                                    | E_R    | 1193.65| 993.40| 1153.88| 1221.37|
|                                    | E_T    | 797.77| 564.87| 707.97| 839.00|
| Specific longitudinal modulus of   | E_L/ρ  | 25.09| 23.09| 22.93| 17.08|
| elasticity (GPa·g⁻¹·cm³)          | E_R/ρ  | 2.92 | 2.43 | 2.76 | 2.98 |
|                                    | E_T/ρ  | 3.36 | 3.01 | 3.10 | 3.43 |
|                                    | GRT/ρ  | 781.05| 599.95| 711.80| 670.03|
| Shear Modulus (MPa)                | G_LR   | 1007.50| 759.28| 899.97| 1030.85|
|                                    | G_LT   | 937.12| 735.15| 898.57| 845.08|
| Specific shear modulus of          | G_RT/ρ | 1.91 | 1.47 | 1.70 | 1.63 |
| elasticity (GPa·g⁻¹·cm³)          | G_LR/ρ | 2.47 | 1.86 | 2.15 | 2.51 |
|                                    | G_LT/ρ | 2.29 | 1.80 | 2.15 | 2.06 |
|                                    | G_RT   | 0.46 | 0.47 | 0.46 | 0.44 |
| Poisson Coefficient                | υ_LR   | 0.43 | 0.44 | 0.43 | 0.40 |
|                                    | υ_RT   | −0.38| −0.29| −0.33| −0.59|

Table 6. The results of the multifactorial discriminant analysis of the acoustic and elastic parameters in relation to the music spruce wood grade.

| Variables | Wilks’ Lambda | Partial Lambda | F-Remove | Significance p-Level | Tolerance |
|-----------|---------------|----------------|----------|----------------------|-----------|
| VLL (m/s) | 0.1502        | 0.5900         | 3.7060   | 0.0337               | 0.0278    |
| VRR (m/s) | 0.1886        | 0.4700         | 6.0140   | 0.0060               | 0.0378    |
| υ_LR      | 0.1829        | 0.4846         | 5.6714   | 0.0076               | 0.0108    |
| E_L (MPa)  | 0.1147        | 0.7726         | 1.5692   | 0.2357               | 0.6033    |
| ρ (kg/m³)  | 0.0842        | 0.9489         | 0.2636   | 0.8505               | 0.7790    |
| VTT (m/s)  | 0.0682        | 0.7691         | 1.5044   | 0.2549               | 0.2098    |
| E_R (MPa)  | 0.0847        | 0.9556         | 0.2320   | 0.8726               | 0.0802    |
| E_T (MPa)  | 0.0738        | 0.8327         | 1.0045   | 0.4179               | 0.0920    |
| υ_LT       | 0.0765        | 0.8635         | 0.7902   | 0.5179               | 0.0891    |
| υ_RT       | 0.0744        | 0.8399         | 0.9528   | 0.4402               | 0.7053    |
| G_RT (MPa) | 0.0876        | 0.9883         | 0.0591   | 0.9804               | 0.5677    |
| G_LR (MPa) | 0.0774        | 0.8737         | 0.7226   | 0.5539               | 0.1163    |
| G_LT (MPa) | 0.0879        | 0.9917         | 0.0417   | 0.9881               | 0.5541    |
The statistically significant relationships ($p \leq 0.05$) found are of moderate to strong intensity. The wood density is statistically inconsistent with any of the measured parameters. The acoustic sound velocity in the transverse direction in the wood (radial and tangential) correlates better with the other determined parameters than the sound velocity in the longitudinal direction of the spruce wood sample (Figure 7a). The closest links are between the shear moduli in the three directions of anisotropy and between them with the velocities in the radial and tangential directions of wood (Figure 7c). The highest correlation coefficient is between $v_{LR}$ and $v_{LT}$: Spearman $R = +0.962$, $p < 0.0001$ (Figure 7d). Thus, it is worth mentioning that the characteristics of the annual rings are associated with the acoustic parameters in the radial direction, not those in the longitudinal direction. The regularity of the rings and their components are the characteristics of the rings with the greatest acoustic relevance; up to an average annual ring width of 2–2.5 mm, the size of the acoustic parameters increases with the width of the rings. Between the four quality classes for the anatomical structure of resonant spruce wood, the differences are sensitive, with their variability increasing with the decrease in the quality class (from A to D).

3.2.2. Principal Component Analysis (PCA)

The PCA maximizes the correlations of the object scores with each of the quantified variables for the number of components. Therefore, in the factorial analysis five main
components were extracted, the first two together explaining 58% of the total variance. The first main component is defined by the Young’s modulus in the radial direction \( E_R \) and by the sound velocity in the tangential direction of spruce wood \( V_{TT} \); the second component is defined by the sound velocity in the longitudinal direction of spruce wood \( V_{LL} \) and the quality class (Figure 8).

![Figure 8](image-url)

**Figure 8.** The physical, acoustic, and elastic parameters in the 1,2 plane of the PCA. Legend: grade, the quality class of resonant spruce wood; RI, the ring width regularity index; TRW, the annual ring width; \( b^* \), color yellowness; WD, wood density; \( E_L \), Young’s modulus along the wood fibers; \( V_{RT} \) and \( \nu_{LT} \), Poisson coefficients; \( V_{LL} \), sound velocity in the longitudinal direction of the wood; \( V_{TT} \), sound velocity in the tangential direction of the wood; \( E_R \), Young’s modulus in the radial direction of wood.

The other parameters \( G_{LR}, V_{TT}, E_R, \) and \( G_{LT} \) vary in tandem with the proportion of late wood and the color brightness and redness. The density of wood is diametrically opposed to all these variables. It was observed that the quality class of the wood, defined according to anatomical patterns, is well represented by the Poisson coefficient \( \nu_{LT} \)—with which it varies in the same direction—as well as by the average annual ring width TRW and the quality class (A, B, C, and D), with which it varies in the opposite direction. Additionally, it resulted that TRW, the ring widths regularity index RI, the quality class, and the color yellowness are closely related to each other. The density of wood is far from all the other measured physical and acoustic characteristics.

### 3.2.3. Correlations between Elastic–Acoustic Properties and Anatomical Features of Resonant Spruce

The links between the physical characteristics and the acoustic/elastic characteristics of the examined spruce wood are generally of low to moderate strength, as can be seen in Table 7. The physical characteristics of wood, especially its structure, are most closely related to the sound speed along the wood fibers. Thus, in Figure 9 it can be observed that the sound speed along the wood fiber \( V_{LL} \) decreases with the increase in the width of the
annual rings, with these delimiting the anatomical models of the wood and, implicitly, the quality classes. However, the sound velocity in the radial direction ($V_{RR}$) is independent of the variables of the structure and color of wood. The sound velocity in the tangential direction ($V_{TT}$) increases slightly and insignificantly with the width of the rings and its components (early wood and late wood).

Table 7. Coefficient matrix of Spearman simple correlation between acoustic parameters and the physical and structural characteristics of the material (legend: values marked with bold are significant at $p < 0.05$).

| Variables | TRW  | RI   | LWW  | LWP  | $L^*$ | $a^*$ | $b^*$ |
|-----------|------|------|------|------|-------|-------|-------|
| $\rho$ (kg/m$^3$) | 0.396 | 0.399 | 0.402 | -0.293 | -0.021 | -0.160 | 0.421 |
| $V_{LL}$ (m/s) | -0.708 | -0.639 | -0.708 | 0.229 | 0.259 | -0.021 | -0.350 |
| $V_{RR}$ (m/s) | 0.057 | -0.012 | 0.075 | 0.253 | 0.021 | -0.253 | 0.058 |
| $V_{TT}$ (m/s) | 0.289 | 0.217 | 0.258 | 0.214 | 0.150 | -0.238 | 0.117 |
| $E_L$ (MPa) | -0.287 | -0.273 | -0.339 | 0.125 | 0.336 | -0.440 | 0.070 |
| $E_R$ (MPa) | -0.184 | -0.239 | -0.166 | 0.123 | -0.093 | 0.216 | -0.245 |
| $E_T$ (MPa) | -0.065 | -0.147 | -0.088 | 0.162 | -0.007 | 0.186 | -0.234 |
| $C_{LT}$ (MPa) | -0.230 | -0.259 | -0.186 | 0.247 | 0.059 | -0.153 | -0.110 |
| $C_{LR}$ (MPa) | 0.244 | 0.171 | 0.248 | 0.292 | 0.057 | -0.351 | 0.199 |
| $C_{RT}$ (MPa) | -0.117 | -0.127 | -0.062 | 0.210 | 0.011 | -0.084 | -0.094 |

The size of the elasticity modulus in the longitudinal direction ($E_L$) decreases with the redness of the wood color. This relationship is due to the influence that the size of the late wood would have on the color of the wood. In fact, the redness color has nothing to do with the late wood width (Spearman $R = -0.086, p = 0.69$) or with the proportion of late wood ($R = -0.148, p = 0.49$). The wood density’s relationship with the yellowness could be explained by the surprising positive contribution of the early wood thickness to the wood density ($R = +0.421, p = 0.04$). Additionally, the regularity of the annual rings is directly proportional to the width of the rings ($R = +0.994, p < 0.001$) due to the restrictive way the quality classes are formed. From the analysis performed by [12–16,19–23], it is evident that the absolute width is not as important an index of wood in terms of the sound produced as the regularity in the radial direction.

Figure 9. The regression between the sound velocity in the longitudinal direction and the annual ring width.
4. Conclusions

This paper aimed to determine the acoustic and elastic characteristics of resonant spruce wood and correlate them with the anatomical patterns of tonewood, which was classified into four quality classes, according to its use by violin manufacturers. The statistical correlations between the different anatomical parameters of the wood and the acoustic/elastic parameters highlighted the fact that:

- The anisotropy of spruce wood is the largest in the tangential direction, with the modulus of longitudinal elasticity in the tangential direction registering the largest dispersion.
- The speed of sound propagation in radial direction $V_{RR}$, Poisson’s ratio $\nu_{LR}$, the speed of propagation of sounds in the longitudinal direction $V_{LL}$, and the longitudinal elasticity modulus $E_L$ are the most important properties that differentiate the quality classes of resonant spruce.
- $V_{LL}$ is the variable that best expresses the links between the acoustic–elastic properties and the physical properties of the material; it defines the second main component (Figure 9) and correlates much better than $V_{RR}$ with the physical properties of wood (see new Table 7). Instead, $V_{RR}$ is best able to distinguish the quality classes of violins (Table 6).
- Among the parameters analyzed, the best correlation was obtained between the speed of sound in the radial and tangential directions and the other physical and elastic parameters.
- Regarding the correlation between the color of the wood and the elastic properties, it was observed that the modulus of elasticity in the longitudinal direction ($E_L$) decreases with the redness of the wood color.

The presented research highlights the fact that the extreme scarcity of this raw material that has the features of regularity in the structure of the annual rings, a lack of defects, and acoustic/elastic properties that are correlated with desirable physical ones makes it very valuable for violin producers. As a result, the quality of resonant wood is reflected by the prices applied to the finished product (violin).

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Data Availability Statement: Details regarding where data supporting reported results can be found on https://minovis.unitbv.ro/ (accessed on 18 August 2021).

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