Physical and mechanical characterization of resonance spruce (Picea Abies L)

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Abstract. The aim of the paper is to present the experimental results related to physical and mechanical characteristics of resonance wood, one of the most qualitative wood material. Resonance wood, mainly spruce (Picea abies L) is used for musical instruments manufacturing and Romania is well known for resonance wood located in Gurghiu Mountains. Physical features of resonance spruce in terms of colour, ring width, ring regularity, latewood proportion and density were determined on samples provided by musical instruments factory from Reghin. The density profile of resonance spruce samples was determined using the X-Ray Density Profile Analyzer DPX300 and color of samples was obtained by means of chroma meter CR-400 Konica Minolta. Mechanical properties as elasticity modulus, viscous modulus, damping were obtained using dynamic mechanical analysis (DMA).

1. Introduction
The acoustic quality of the violin models made by Romanian manufacturers from Romanian resonance wood, with Romanian craftsmanship and Romanian technical culture - all preserved in the heart of Romania, in the city of violins – Reghin. Its reputation grew continuously until it became an internationally recognized manufacturer for violins of exceptional acoustic and aesthetic quality. The essayist Mircea Oprița mentioned: “It seems that we, the Romanians, have an involvement in the old industry of brilliant instruments, as evidence was found that the wood for the Stradivari and Amati violins came from the forests of Bucovina, in the Putna region. The wood was cut and processed by the local monks according to a mystical ritual. The traces of the trade with violin wood from Bucovina can be followed up to Vienna and further on, to Cremona. The ritualistic rigor by which the tree was chosen for the face of the violin (Pinus cembra) and its solitary pair, a silver maple from which the back of the instrument was made, is most interesting” (http://www.descopera.ro/cultura/2306122-lemnul-care-canta). The sound of the heritage violins manufactured by the great masters of Cremona - Stradivari, Guarneri, Amati - are considered the highest level of violin art for which, even after a few centuries, they are still used as a model by the current violin producers [1]. Some studies have highlighted the importance of the quality of the resonance wood used in the construction of musical instruments [2–4], others have analyzed by means of modern techniques the vibrations of the violin body, determining the frequencies and the natural modes [5–7], other researches have focused on the acoustic characteristics of the heritage violins determined under both conditions: laboratory as well as in real conditions of use by artists. It is a certain fact that all the studies undertaken in international
COST-type projects compared under all the above-mentioned aspects the structural, geometrical, modal and acoustic characteristics of heritage violins with those of current ones, without offering technical solutions to improve the acoustic quality of violins by modifying some technological parameters [8–10]. Both constructively and acoustically, the violin is considered the queen of musical instruments. The constructive complexity starts from the stage of harvesting the resonance wood considering that its structural characteristics are not acquired genetically, but they result from the combined action of several (climatic, edaphic, orographic, biotic, anthropic) factors, that influence the formation of a special kind of wood, with special acoustic properties. In our country, the main growth area of resonance spruce trees is in the northern part of the Eastern Carpathians, the most famous being the forest districts Moldovita and Tomnatic [11, 12]. The aim of this paper is to present the experimental results related to physical and mechanical characteristics of resonance spruce, one of the most qualitative wood material used for strings and bowed instruments.

2. Materials and methods

2.1. Methods
The physical features of resonance spruce in terms of ring width, ring regularity, latewood proportion and density were determined using WinDENDRO Density image-analysis system (Régent Instruments, 2007). The samples were scanned at a resolution of 2200 dpi. The width of the annual rings was measured digitally in cross section of spruce samples. The measurements were performed with an accuracy of 0.001 mm. The database, originally in .txt format, was imported and processed primarily in Microsoft Excel. The equipment of X-Ray Density Profile Analyzer DPX300 was used to determine the density. The samples with the dimensions 50x50x30 mm³ were automatically weighed and measured tested by the equipment devices. After that, each specimen was introduced in the X-ray device train where the equipment measured the density profile using the X-ray flux. For mechanical properties, the method of dynamic mechanical analysis (DMA 242C Netzsch equipment) consists in applying of an oscillating force at different frequency of 1 Hz (the amplitude of force 6N and maximum deflection 30 μm), in two cases: firstly, isotherm measurement at 30±0.10°C (temperature was kept constant at 30°C during the test) and secondly, temperatures varying in the range 30°C and 120°C for 30 minutes (figure 1). In figure 1 can be seen the experimental equipment which performs the three points bending flexural test The device consists of: upper part of DMA (force sensor and signal, displacement sensor and signal, oscillator, automatic adjustment), 1 – sample, 2 - supports for three points bending, 3 – force sensor and signal, 4 - sample thermocouple, 5 - conditioner chamber, data acquisition system and display.

![Figure 1. Experimental equipment for dynamical mechanical analysis: 1 – sample; 2 – supports; 3 – head for loading; 4 – thermocouple; 5 - conditioner chamber.](image-url)
2.2. Materials
Due to the wood grading in the manufacture of musical instruments, spruce wood samples were classified in following categories: class A - samples with dense fibres, in radial direction (coded 17.1 – 17.4), class B - samples with rare fibres, in radial direction (coded 18.1 – 18.4), class C - samples with dense fibres, in semiradial direction (coded 19.1 – 19.4), class D - samples with rare fibres, in semiradial direction (coded 20.1 – 20.4) (figure 2). The physical characteristics of samples for DMA are presented in table 1.

![Figure 2. The samples for DMA.](image)

| Sample Code | Structure | Width b [mm] | Length L [mm] | Thickness h [mm] | Mass [g] | Moisture Content MC [%] | Average values of density [g/cm³] | STDV |
|-------------|-----------|--------------|---------------|-----------------|---------|------------------------|---------------------------------|------|
| 17.1        | A         | 10.42        | 49.98         | 4.67            | 1.23    | 6.1                    | 0.505                           | 0.00288 |
| 17.2        | Dense fibres | 10.48        | 50.04         | 4.68            | 1.14    | 6.4                    | 0.464                           | 0.00277 |
| 17.3        | Radial    | 10.42        | 50.04         | 4.64            | 1.13    | 6.5                    | 0.467                           | 0.00225 |
| 17.4        | section   | 10.49        | 49.98         | 4.70            | 1.25    | 6.3                    | 0.507                           | 0.00269 |
| 18.1        | B         | 10.41        | 50.08         | 4.51            | 0.75    | 6.2                    | 0.318                           | 0.00168 |
| 18.2        | Rare fibres | 10.44        | 50.10         | 4.53            | 0.83    | 6.4                    | 0.35                            | 0.00180 |
| 18.3        | Radial    | 10.35        | 49.91         | 4.54            | 0.74    | 6.7                    | 0.315                           | 0.00198 |
| 18.4        | section   | 10.37        | 49.95         | 4.52            | 0.79    | 6.3                    | 0.337                           | 0.00179 |
| 19.1        | C         | 10.50        | 50.00         | 4.52            | 0.99    | 6.4                    | 0.417                           | 0.00208 |
| 19.2        | Dense fibres | 10.51        | 50.00         | 4.53            | 1.00    | 6.5                    | 0.420                           | 0.00189 |
| 19.3        | Semiradial | 10.45        | 49.98         | 4.55            | 0.99    | 6.3                    | 0.416                           | 0.00215 |
| 19.4        | section   | 10.49        | 49.98         | 4.55            | 1.00    | 6.2                    | 0.419                           | 0.00220 |
| 20.1        | D         | 10.45        | 49.89         | 4.52            | 0.79    | 6.2                    | 0.335                           | 0.00264 |
| 20.2        | Rare fibres | 10.44        | 49.99         | 4.49            | 0.88    | 6.4                    | 0.375                           | 0.00275 |
| 20.3        | Semiradial | 10.40        | 49.99         | 4.55            | 0.85    | 6.7                    | 0.359                           | 0.00218 |
| 20.4        | section   | 10.44        | 50.03         | 4.55            | 0.75    | 6.3                    | 0.315                           | 0.00248 |

3. Results and discussion
3.1. X-Ray Density Profile Analyzer
The density profile measured with X Ray Analyzer DPX300 are presented in figure 3. First, the measurements were performed on the three directions of wood related to the x rays flux: radial (figure 4 (a)); tangential (figure 4(b)) and longitudinal (figure 4(c)). In figure 4(a), it can be noticed, the regularity of annual rings and the variation of density with annual ring width, the peaks of curves represent the latewood zones where the density is higher. The variation of density on tangential and longitudinal direction of x rays flux is more smoothness (figure 4(b) and (c)).
Figure 3. The density profile related to direction of x rays flux versus main direction of wood: (a) radial direction; (b) tangential direction; (c) longitudinal direction.

Figure 4. The average values of density for different types of samples.

Because the standard deviation between values for each direction is under 0.0028 g/cm$^3$, in table 1 are presented the average values of density for the three measurements and standard deviation of them. The average values of density for each type of sample are shown in figure 4. It can be noticed that the samples with dense fibers both in radial and semiradial cutting, recorded a density above 0.400 g/cm$^3$ in comparison with the other two types of samples – with rare fibers which have a density between 0.330 and 0.346 g/cm$^3$. These values are similarly with one reported in references [10, 13].

3.2. Density image-analysis

Regarding the structural features of spruce wood, it is known that this specie is formed by 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 woody areas are characterized by low density due to well-developed wood cells, compared to late wooded areas
that have a higher density both due to the period of vegetative dormancy and high lignin content. The small width of the annual rings, their regularity, the proportion of early wood and late wood are characteristics on the basis of which the selection of wood for musical instruments is made. In figure 5 it can be noticed the variation of annual rings width for tested samples. For the high quality of musical instruments, the spruce wood as samples A and C, with annual rings width range between 0.7±0.4 mm for class A and 1.3±0.7 mm for class C are the most wanted wood quality.

![Figure 5. The variation of annual rings width for studied samples.](image)

Because the wood colour is influenced by proportion of early wood and late wood, the analysis of relationship between density and colour wood is presented in figure 6. So, the apparent density of spruce wood forms two clusters centred around 0.39 g/cm³ (samples B and D with relative low density) and 0.44 g/cm³, (respectively, samples A and C) which correspond to different concentrations of red in the colour of the wood. The similar observation was obtained by [14].

![Figure 6. The variation of greenness scale related to apparent density of spruce wood.](image)
3.3. Dynamic mechanical analysis

3.3.1. Constant temperature. The DMA offers the viscous and elastic response of the material as a function of temperature and frequency. Corresponding deformation of a viscoelastic deformation can be separated into in-phase and out of phase. The sum vector of the two components is complex strain denoted with $E^*$ and the terms $E'$ and $E''$ are called conservation (storage) modulus and loss modulus. The ratio between loss modulus and the storage modulus represents the damping coefficient or capacity of material to store strain energy. Expressing the deformation as a function of time, follows: $\varepsilon(t) = E^*\varepsilon_0\sin(\omega t)$, where $\varepsilon$ is the strain at time $t$; $E$ – elasticity modulus, $\varepsilon_0$ - maximum stress; $\omega$ - frequency of oscillation. The program returns the values of $E'$ and $E''$. In case of resonance spruce, it can be noticed that the storage modulus $E''$ increases slowly with increasing the testing time, in isothermal conditions, at temperature of 30°C (figure 7(a)). The higher values of storage modulus are recorded in case of samples cut in radial direction of wood (see sample A and B). The sample denoted D, characterized by rare fibres, semiradial section, recorded the values of storage modulus with 16.6% lower than samples A and B, and sample C – with 26.6% lower than samples A and B (figure 8). So, both the proportion of late wood and early wood, and the section of wood samples related to loading influence the elastic behavior of wood. So, if the wood is cut perfect in radial direction, the annual rings with alternating zone of early wood and late wood behaves similarly with multilayers composites, the rigidity being higher in comparison with semiradial direction where the layers are more or less inclined reported to loading direction (figure 8(b)). In figure 7(b), the variation of loss modulus can be observed for all four types of samples. The viscous behavior of each type of spruce sample is more obvious. For musical instruments, the capacity of wood to store energy and recover elastically, is very important because the acoustic quality depends on these characteristics. Decreasing of loss modulus for all types of samples indicates that all testes wood specimens are proper for manufacturing the violin or guitar. The decreasing of damping during the loading exposure, as can be noticed in figure 8(a), confirm that vibrational and acoustical capacity of resonance wood increasing with playing to the musical instruments, in mechanical meaning, to stress the wood at low intensity of loading.

![Figure 7](image1.png)

**Figure 7.** (a) The variation of storage modulus in time; (b) the variation of loss modulus.

![Figure 8](image2.png)

**Figure 8.** (a) The variation of damping coefficient in time; (b) the position of early wood and late wood layers reported to loading direction.
3.3.2. Temperature variation. The wood is composed by different types of chemical components which in case of spruce wood are in proportion of 54% (cellulose), 18.5% (hemicelluloses), 25.4% (lignin), 0.97% (extractives) and 0.28% (ash) [10]. Some references considered that the viscous - elastic behavior of wood subjected to constant loading in elastic domain, is affect by temperature which stabilized the internal stresses [10, 13]. DMA tests revealed that the complex modulus for all specimens recorded an increasing with increasing the temperature. The increasing rate of complex modulus is much more obvious for samples with dense fiber (small widths of annual rings) and disposed in radial direction in comparison with semiradial fibers of samples (code B and D (figure 9)). This tendency is caused by the higher lignin content in the structure of the samples, which begins to undergo a crosslinking process, thus increasing the rigidity of the wood. The damping coefficient variation (especially the peak) indicates the temperature value which some modifications of chemical wood are produced. So, the samples cut in radial direction, even with dense or rare fibers, have an homogenous trend line of damping variation, with a peak around 60 – 70°C and suddenly decreasing (figure 10(a)). The samples C and D, cut in semiradial direction (semi-tangential), are heterogeneous behavior and with different temperature transition, sample C (80 – 85°C) and sample D (55 – 60°C) (figure 10(b)).

**Figure 9.** The variation of complex modulus with temperature: (a) samples cut in radial direction; (b) samples cut in semiradial direction.

**Figure 10.** The variation of damping coefficient with temperature: (a) samples cut in radial direction; (b) samples cut in semiradial direction.

4. Conclusions
The paper presents the experimental investigation of physical and mechanical properties of resonance spruce. Thus, the structure of wood in terms of proportion of early wood and late wood influence the density and colour of wood. The density of spruce samples with annual rings width of 0.7±0.4 mm and
almost 30% latewood proportion recorded an apparent density of 0.45 g/cm³, since the samples with annual rings width of 1.3±0.7 mm and late wood proportion of almost 20%, have low density around 0.33 g/cm³. Regarding the colour of wood, the spruce with higher proportion of late wood and high density, have red scale range between 2.5 – 2.9.

Viscous elastic properties of resonance spruce are more influenced by the section of wood reported to direction of loading, in this case the wood have similar behaviour with a multilayers composite disposed with higher inertia moment on the load direction. Storage modulus measured in isothermal condition with 1Hz loading frequency and 6N the intensity, range between 4500MPa and 6300MPa. With increasing temperature, the complex modulus increase to with a rate of 13MPa/°C. The first transition temperature recorded for spruce wood is around 60-80°C, but in this stage, cannot be mention glass transition.

5. References

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