Experimental Modal Analysis of Violin Bodies with Different Structural Patterns of Resonance Spruce

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Abstract. The paper aims to highlight the modal response of violin bodies made of four quality classes of resonant wood, following the anatomical structure of the wood. The four categories of musical instruments, made at the S.C. Gliga Instrumente Muzicale S.A., were excited by an impact hammer type B&K 8204 and its response was captured by an accelerometer type B&K 4517-002 (Brüel & Kjær, Denmark, Nærum). The received signals were transmitted through a conditioning device to a Dynamic Signal Acquisition System (DAQ) - NI USB-9233 (National Instruments, USA, Austin), connected to a laptop. The obtained signals were in the form of the natural frequencies and the damping factor. The results highlighted the nonlinear and inhomogeneous behavior of violins with different structural patterns, proving that their vibrations depend on many factors.

1. Introduction

In the construction of violins, the front plates are made of spruce wood and the back plates of maple wood, these lignocellulosic materials having the physical, mechanical and acoustic characteristics of the resonant wood, being a wood without structural defects. Depending on the regularity of the annual rings, their width, the proportion of early wood-late wood, the resonant spruce plates belong to some structural models established in the literature [1 – 4]. For back plates, curly fiber maple is mainly used, but straight fiber maple wood is accepted for certain categories of pieces. The way the violin produces sounds is similar to stringed instruments (guitar), with the fact that the vibration of the string is produced by the bow rubbing the string. Between the bow and the excited string there is an angle that decomposes the force produced by the bow in the horizontal plane into a longitudinal component (parallel to the string) and a transverse one, on the string [5 – 7]. The string begins to vibrate both in the transverse plane (in the direction of force application by the bow) and in the longitudinal plane - along the string), the transverse vibrations being transmitted through the callus to the violin and further to the volume of air in the violin body, which behaves like a Helmholtz-type resonator, thus forming compression and expansion waves between the front, back and eclipses of the violin body, that produces an intense sound. Radiation intensification also explains the increase in sound intensity in the case of system resonance. The fundamental frequencies are related to the geometric characteristics of...
the source from which the wave propagates, and the set of harmonics (timbre) is dependent on the resonator that amplifies the initial sound, adding a series of its own frequencies [8, 9]. The study focused on determining the frequency spectrum, eigenfrequencies and damping factor of four different types of violins in terms of the structure of the resonant wood.

2. Materials and methods

2.1. Materials
The types of violins studied were produced at the S.C.Gliga Instrumente Muzicale S.A. musical instrument factory. According to their classification, there are four groups coded as follows: Maestro class violins - code A00C1 and A00C2; Professional class violins - code B00C1 and B00C2; Student class violins - code C00C1 and C00C2; School class violins - code D00C1 and D00C2. The difference between these is the structure of the wood used for the violin faces and the back of the violin. Thus, 8 violins were analyzed, two from each structural wood quality class (figure 1). In figure 1, it can seen the different structures of wood for the four classes of violins in terms of the width of the annual rings, the ratio of early wood and late wood, for spruce, and for maple, the degree of the curly fiber.

![Figure 1. Structural characteristics of the violin classes analyzed: a) class A - Maestro; b) class B - Professional; c) class C - Student; d) Class D - School. Left: cross-sectional view of resonant spruce wood; Right - view in the longitudinal radial section of maple wood.](image-url)
To identify the structural characteristics of the wood, the measurements were made on samples in the form of cubes, with a side size of 30 mm, 5 samples from each category (A, B, C, D) and from each species, so a total number of 40 specimens. The physical and geometric characteristics are presented in tables 1 and 2. The modal analysis was performed on violins with neck, having the structural models of the wood according to classes A, B, C, D. The values regarding the mass of the plates and the mass of the body of the violin without neck and with neck are centralized in table 3. The plates, as individual structures, have been analyzed in previous authors' studies [10 – 12]. It is observed that the mass of the tested samples increased with the complexity of the structure in different technological stages.

### Table 1. Physical characteristics of the specimens used for the structural analysis of resonant spruce wood.

| Specimen quality | Sample no. | Length l [mm] | Thickness h [mm] | Width b [mm] | Mass m [kg] | Apparent density [g / cm³] |
|------------------|------------|---------------|-----------------|--------------|-------------|---------------------------|
| A 1              | 30.75      | 30.02         | 30.24           | 12.316       | 0.441       |
| A 2              | 30.51      | 30.35         | 30.40           | 12.292       | 0.437       |
| A 3              | 30.50      | 30.31         | 30.21           | 12.235       | 0.438       |
| A 4              | 30.60      | 30.24         | 30.38           | 12.287       | 0.437       |
| A 5              | 29.84      | 30.13         | 30.48           | 11.949       | 0.436       |
| B 1              | 30.29      | 30.22         | 30.02           | 10.592       | 0.385       |
| B 2              | 30.27      | 30.25         | 30.09           | 10.453       | 0.379       |
| B 3              | 30.73      | 30.33         | 30.19           | 10.608       | 0.377       |
| B 4              | 30.57      | 30.43         | 30.02           | 10.787       | 0.386       |
| B 5              | 30.43      | 30.36         | 30.13           | 10.528       | 0.378       |
| C 1              | 30.28      | 30.33         | 30.49           | 12.697       | 0.453       |
| C 2              | 30.18      | 30.34         | 30.60           | 12.654       | 0.452       |
| C 3              | 30.13      | 30.28         | 30.10           | 12.09        | 0.440       |
| C 4              | 30.48      | 30.70         | 30.82           | 12.499       | 0.433       |
| C 5              | 30.15      | 30.33         | 30.54           | 12.592       | 0.451       |
| D 1              | 30.16      | 30.13         | 30.53           | 10.92        | 0.394       |
| D 2              | 30.3       | 30.31         | 30.29           | 11.141       | 0.400       |
| D 3              | 30.35      | 30.25         | 30.39           | 10.962       | 0.393       |
| D 4              | 31.08      | 30.25         | 30.35           | 11.151       | 0.391       |
| D 5              | 30.66      | 30.48         | 30.05           | 11.102       | 0.395       |

### Table 2. Physical characteristics of the specimens used for the structural analysis of the resonant maple wood.

| Specimen quality | Sample no. | Length l [mm] | Thickness h [mm] | Width b [mm] | Mass m [kg] | Apparent density [g / cm³] |
|------------------|------------|---------------|-----------------|--------------|-------------|---------------------------|
| A 1              | 29.26      | 30.31         | 30.21           | 14.901       | 0.556       |
| A 2              | 29.41      | 30.17         | 30.32           | 15.069       | 0.560       |
| A 3              | 29.84      | 30.28         | 30.42           | 15.285       | 0.556       |
| A 4              | 29.25      | 30.45         | 30.44           | 15.071       | 0.556       |
| A 5              | 29.81      | 30.64         | 30.46           | 15.433       | 0.555       |
| B 1              | 30.03      | 30.15         | 30.17           | 15.850       | 0.580       |
| B 2              | 30.00      | 30.45         | 30.31           | 15.764       | 0.569       |
| B 3              | 29.85      | 30.18         | 30.15           | 15.778       | 0.581       |
| B 4              | 29.85      | 30.07         | 30.10           | 15.781       | 0.584       |
| B 5              | 30.25      | 30.04         | 30.24           | 15.928       | 0.580       |
| C 1              | 29.76      | 30.25         | 30.41           | 15.973       | 0.583       |
| C 2              | 29.78      | 30.21         | 30.30           | 15.934       | 0.585       |
Table 3. Physical characteristics of violin bodies.

| Plate code (F- face plate; S - back plate) | Mass [g] | Violin body code | Mass of neckless violin body [g] | Mass of violin body with neck [g] |
|------------------------------------------|----------|-----------------|----------------------------------|---------------------------------|
| A00F1                                    | 76       | A00C1           | 243                              | 328                             |
| A00S1                                    | 114      |                 |                                  |                                 |
| A00F2                                    | 85       | A00C2           | 251                              | 323                             |
| A00S2                                    | 129      |                 |                                  |                                 |
| B00F1                                    | 86       | B00C1           | 261                              | 321                             |
| B00F2                                    | 85       | B00C2           | 253                              | 313                             |
| B00S1                                    | 136      |                 |                                  |                                 |
| B00S2                                    | 131      |                 |                                  |                                 |
| C00F1                                    | 93       | C00C1           | 267                              | 329                             |
| C00S1                                    | 90       |                 |                                  |                                 |
| C00F2                                    | 135      |                 |                                  |                                 |
| C00S2                                    | 128      | C00C2           | 257                              | 320                             |
| D00F1                                    | 86       | D00C1           | 236                              | 294                             |
| D00S1                                    | 86       |                 |                                  |                                 |
| D00F2                                    | 112      |                 |                                  |                                 |
| D00S2                                    | 116      | D00C2           | 244                              | 305                             |

2.2. Experimental methods

2.2.1. Identification of structural patterns of resonance wood. The annual rings and wavelength of the corrugated fiber were digitized using WinDENDRO Density 2007 image-analysis system (WinDENDRO 2007). For this purpose, the samples were scanned at a resolution of 2200 dpi. The image analysis allowed the automatic detection of the annual rings, but also the corrective intervention of the operator. The characteristics of the annual rings were measured in the radial direction, on the cross section, and the wavelength, in the tangential direction, on the radial section. The measurements were performed with an accuracy of 0.001 mm.

In the case of spruce, once the annual rings were identified, the early wood was digitally separated from the late wood. For the maple, the width of the annual ring and the wavelength of the crude fiber were measured. The following variables resulted from the measurements on the wood structure: the total width of the annual ring (TRW), the width of the early wood (EWW), the width of the late wood (LWW), the early wood proportion (EWP), the late wood proportion (LWP) and the curly maple wavelength (CWL) [10].

2.2.2. Modal analysis. The test method used in this research consisted of a dynamic analysis to determine the frequency response, applied to violin bodies belonging to the four classes of structural quality of wood, placed on an elastic structure, as can be seen in figure 2.
Figure 2. Experimental set-up: 1 – tested violin; 2 – elastic support; 3 – accelerometers; 4 – microphone; 5 – impact hammer; 6 – data acquisition system; 7 – laptop.

The excitation of the structures was done with the impact hammer for light structures type B&K 8204, the vibrations of the front and rear plates being captured with accelerometers type B&K 4517-002 fixed on the two plates. The air vibrations in the form of sound pressure were acquired through the microphone type PCB 130E20 ICP®, the generated signals were then transmitted via a signal conditioning device to the NI USB-9233 dynamic data acquisition board produced by National Instruments (Austin, USA), connected to a laptop. The signal was viewed using a special application developed in NI-LabVIEW ©, and the graphic data was processed using the MATLAB © program. The principle of the experiment is presented in figure 2.

3. Results and discussions

3.1. Identification of structural models of wood

The way of grouping the values of the wood structure indicators in relation to the predefined quality classes was statistically verified. Figure 3 shows the variations in the width of the annual rings for spruce wood (figure 3(a)) and maple wood (figure 3(b)). As the wavelength of the fiber ripples in the maple wood increases, so does the brightness of the wood (figure 3(c)). It is observed that, for spruce wood, the width of the annual rings is grouped in the four quality classes, compared to maple wood where the width of the annual rings is heterogeneous in relation to the quality class. Thus, it turned out that all the variables involved in the study are stratified according to the quality class to which the sample belongs (table 4). For spruce, the absolute values of the annual ring indicators ensure a better discrimination of the quality classes than the relative values. For maple, there is a tendency to increase the width of the rings and to decrease the wavelength with the improvement of the quality class. Quality class C stands out: for this class, the amplitude of values is higher. For maple, there is a tendency to increase the width of the rings and to decrease the wavelength with the improvement of the quality class. Quality class C stands out again: for this class, the amplitude of values is also higher. Despite the limited degree of variation, the density of wood can be stratified by structural quality class in both species. Spruce wood of quality classes A and C is heavier, by about 60 kg / m3, than wood of classes B and D. For maple, the wood is significantly lighter in the samples of class A quality.
Figure 3. Variation of the width of the annual rings between the four classes of structural models of wood: a) spruce samples; b) maple samples; c) wavelength of the curly fiber.
Table 4. Statistical verification of the possibility of stratifying the characteristics of the examined wood according to the proposed quality classes [10, 12].

| Species of the sample | Wood variable                  | Statistical significance of differences between quality classes | Stratification of values by quality class... | Quartile interval |
|-----------------------|--------------------------------|-----------------------------------------------------------------|---------------------------------------------|-------------------|
|                       |                                | The test Kruskall-Wallis/ANOVA                                   | A               | B               | C               | D               |
| Spruce                | Annual ring width [mm]         | H, F, p                                                         | 0.59...0.85    | 1.22...1.51     | 1.50...1.89     | 1.98...2.60     |
|                       | Early wood width [mm]          |                                                                  | 0.44...0.66    | 0.97...1.17     | 1.18...1.48     | 1.52...1.99     |
|                       | Late wood width [mm]           |                                                                  | 0.14...0.21    | 0.23...0.35     | 0.29...0.45     | 0.42...0.62     |
|                       | Proportion of early wood [%]   |                                                                  | 70.94...79.51  | 75.76...80.56   | 76.24...81.74   | 74.33...79.22   |
|                       | Proportion of late wood [%]    |                                                                  | 20.50...29.07  | 19.44...24.24   | 18.27...23.76   | 20.78...25.67   |
|                       | Apparent density [g/cm³]       |                                                                  | 0.437...0.438  | 0.378...0.385   | 0.440...0.452   | 0.393...0.395   |
| Maple                 | Annual ring width [mm]         |                                                                  | 0.92...1.56    | 0.82...1.41     | 0.57...1.08     | 0.71...1.28     |
|                       | Curly fiber wavelength [mm]    |                                                                  | 4.26...6.96    | 5.36...7.16     | 6.28...9.43     | -               |

3.2. Time frequency analysis

In the modal analysis, time and frequency signals were extracted, resulting in the frequency spectrum for spruce plates, maple wood plates and air inside the violin body and the damping factor for each analyzed component, as it can be observed in figures 4 – 7.

It is found that the first fundamental frequency has the same value for all three analysed components: spruce board, back plate and air, regardless of the structural model of the wood and the quality class. In the case of spruce plate, the value is not the same for the four classes A, B, C, D. Thus, for class A, the fundamental frequency recorded is 244.1 Hz, while in the case of the other classes, the value is in around 250 Hz. The maple wood back plate shows variations in the fundamental frequency in relation to the quality class of the wood, with an inhomogeneous response. For example, Class B back plates recorded values of 256.3 Hz (B00C1) and 244.1 Hz (B00C2), respectively. A tendency to increase the value of the fundamental frequency is registered for the class C violins where the back plates have their first own frequency at values of 250 Hz (C00C1) and 256 Hz (C00C2). The 256 Hz value of the C00C2 violin body is also recorded for the spruce top plate. As a result of the interaction of the fluid inside the violin body with the front and back plates, it resulted that the air inside the structure vibrates in the first stage with the same frequency as the spruce plate, regardless of the violin class.

The second eigenfrequency has an interval of one third, ie 1.57 higher than the fundamental frequency, in the case of all quality classes. The dominant frequency differs from one species to another: each plate amplifying differently the vibrations produced in the structure of the violin body. The frequency spectrum differs from one species to another (spruce versus maple), but some values from both the front plate and the back plate are found in the vibrations of the air inside the body. What
is certain is that the dominant frequency of the fluid coincides with its fundamental frequency, the rest of the frequencies having damped values.

Figure 4. Time and frequency analysis for class A violin structures.
Figure 5. Time and frequency analysis for class B violin structures.

The values of the damping factor show a decreasing trend from the front plate, the back plate and the lowest value is recorded for the air inside the body. From the point of view of the quality class, with the lowest values they are registered for class A (83/68/46 - A00C1; 61/54/41 - A00C2) (figure 4), and the maximum values are registered in the case of the bodies from category C (112 / 57/45 - C00C1; 109/67/53 - C00C2) (figure 6).
Figure 6. Time and frequency analysis for class C violin structures.
Figure 7. Time and frequency analysis for class D violin structures.

4. Conclusions

The work aimed to determine the natural frequencies of the boards in the structure of four types of violins, different from each other by the structure of wood. It was found that:

- wood, even if it belongs to the same species, can be classified into structural models according to the anatomical elements, the regularity and width of the annual rings (in the case of spruce wood) or according to the shape of the fibres (curly or straight) in the case of maple wood.
In general, the spectrum is richer in spruce plates than in maple plate or air. This is due to the damping that takes place in the wood, some frequencies of the top plates with small amplitudes are no longer transmitted to the back plates and the air.

- in the spectrum of air frequencies can be identified frequencies of the face and back of the violin.
- considering the experimental method used, the acoustic quality of the violin body cannot be appreciated at this stage.

5. References

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