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Signature Modes of Old and New Violins with Symmetric Anatomical Wood Structure

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Abstract: The paper aims to investigate old and new violins from the perspective of the correlation between the anatomical structure of spruce and maple wood, and the dynamic response of violins. Thus, in the first stage, for each violin, the characteristics of the annual rings were measured on the entire width of the top plate, determining the degree of symmetry of the face with respect to the longitudinal axis of the violin body. Then, each violin was dynamically tested with the impact hammer, determining its own frequency spectrum, mainly the so-called "signature" mode and quality factors. The most important findings consist of identification of the first five modes for old violins, (known as provenance), current new violins, and violins whose origin is unknown, but which could correlate with anatomical, constructive and dynamic characteristics, in order to be able establish origins, and also the measurement of anatomical features of top and back plates in the violins' construction.

Keywords: resonance wood; heritage violin; signature mode; frequencies spectrum

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1. Introduction

In evaluating the timbre of a musical instrument, it is necessary to analyze a number of parameters, among which the sound spectrum and the attack can be mentioned. Today, the violin, thanks to its crystalline timbre, expressive and full of beauty, has remained the most widespread musical instrument in the family of string instruments [1–3]. The general timbre of the violin is well known, with composers asking instrumentalists to use a certain string to enhance a certain type of expressiveness of the melodic lines. According to the conceptualization of violin quality by musicians, the sound of the "E" string (also called cantino) is a bright, luminous chord, the sound of the "A" string is more 'singable', the sound of the "D" string is considered to be the poetic string par excellence, while the sound of the "G" string sometimes has an alto color, and can easily become dramatic, gloomy or dark [4–8].

Numerous studies on resonant wood (spruce or maple) have highlighted both the influence of the physical and mechanical properties of the wood used in the construction of the violin (respectively, density, modulus of elasticity/rigidity, thickness and geometry, and anatomical symmetry of the plates used in the construction of the violins) since, from a mechanical and acoustic point of view, the body of a stringed musical instrument is considered a Helmholtz-type resonator, being a vessel-with-thin-walls type structure, provided with acoustic holes that ensure the oscillating movements of the air inside the vessel [8–13]. The resonating box, composed of the acoustic plate, back and sides (ribs), has the role of amplifying the musical sounds. These elements are made of selected resonant wood or lignocellulosic composite materials with mechanical, elastic and acoustic properties similar to solid wood and able to withstand static and variable stresses specific to musical instruments [13–15].

From a mechanical point of view, the violin is a quasi-symmetrical system that behaves very like a symmetrical system. Theoretical results from symmetric systems cannot be applied to quasi-symmetric systems, but the fact that the properties are very close is shown experimentally for string instruments [16,17]. The violin has a plane of anatomical symmetry that passes through the means of the two plates of the violin body and a longitudinal plane of constructive asymmetry after the bass bar and soundpost has been attached. Both influence the mechanical behavior of violins, as has been shown in various studies [15–19]. Perpendicular to this plane, a plane of constructive quasi-symmetry can also be considered that separates the lower part from the upper part of the violin (Figure 1).

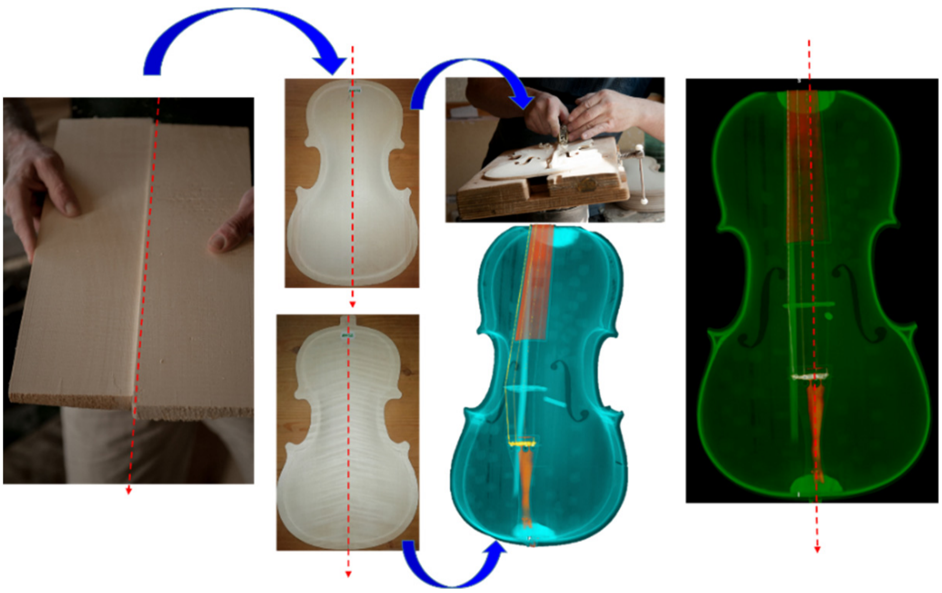


Figure 1. Symmetrical and asymmetrical systems: the violin—anatomical symmetry of the wood and constructive asymmetry of the body.

Regarding old violins, built by well-known luthiers such as Stradivarius, Guarnieri, Amatti, Stainer, Klot and Leeb, there are numerous studies on the structure of wood, its anatomical quality, wood dating, types of varnish used, structural integrity using modern techniques modern, ways of restoration, etc. [18–21]. Many of these musical instruments are rare examples of high artistic mastery and are still used as references in the contemporary manufacture of violins [22–24]. From this aspect, the determining factors have been analyzed over time: the structural quality of wood, moisture content, wood aging, plate geometry (thickness/arching), finishes used, constructive elements (sound post, position and shape of acoustic holes, sounding bar, bridge), and string quality. Other studies have highlighted the effect of aging wood and varnish, the contribution of the primer and even the attack of fungi on the acoustic quality of old violins [25–28]. Studies conducted over time on old and new violins show contradictory results: in some studies, the acoustic and dynamic response of old violins is presented as a standard for the analysis of new ones; in other studies in which the acoustic impressions of soloists were analyzed through blind tests (without the respondents seeing the violins or knowing their history), the results showed that, from the point of view of the acoustic criteria, the new violins present a much more appreciated acoustic quality than the old ones [24,29–33]. The correlations between the signature mode and the modal shapes of the violin body, as well as the connection between the vibrations of the violin plates as individual structures and the plates integrated into the violin body were studied numerically and experimentally by [34–38]. Refs. [3,9,11,34] consider that each violin has only five "signatures": corpus + top + ribs + back as normal modes in the open string region. Refs. [39,40] performed a dynamic analysis of an old historical violin, identifying the cavity modes (A0, A1), corpus modes (CBR or C bouts rhomboidal), and main body resonance (B1− and B1+). Some studies on the modal parameters of unvarnished violins ("white") and varnished violins were made, the "white" instruments being very similar. They noticed that the varnishing did not change the mode shapes but influenced the modal frequencies, especially of modes B(1−) and B(1+).

Nia et al. [39] investigated the evolution of sound hole shape and dimensions from the Late Renaissance to the Late Baroque Period in correlation with air resonance power efficiency, showing that an increasing dimension of the sound hole by roughly 30% across two centuries led to higher air-resonance power, through a corresponding increase of roughly 60%.

The purpose of this analysis was to determine the modal response of violin bodies and to identify the resonant frequencies of different types of violin (old and new) to determine if there are major differences between them. Thus, 11 violins were investigated in terms of air resonance frequency, corpus mode frequency, and main body resonance, in correlation with the degree of symmetry of the anatomical structure of the top plate related to longitudinal axis.

2. Materials and Methods

2.1. Materials

A total of 10 violins were studied: four violins from private persons (artist intrumentakists), containing the label with information on the violin manufacturing date, and belonging to a violin school (Jacobus Stainer violin, 1716; Johann Georg Leeb violin, 1742; Joseph Klotz violin, 1747; Babos Bela violin, 1920), and two violins without a label—for one, its history and the fact that is a copy of a Jacobus Stainer (codenamed "Copy Stainer") were known, and for the other violin (coded "Unbranded"), the origin and membership of a particular school of violinists are not known. Three current violins of maestro class quality were also added to the study, produced at the musical instrument factory "SC Gliga Instrumente Muzicale S.A., Reghin, Romania" (Figure 2). For reference, the Stradivarius–Elder–Voicu 1702 violin, belonging to the cultural heritage of Romania and with the permission of the "George Enescu" Bucharest Philharmonic and master violinist Tomescu Alexandru, was also analyzed.

The same violins were studied in previous research from the points of view of anatomical structures of their wood and of their constructive features [40]. All the violins studied are constructively intact, being used in musical activities by their owners. For this reason, the methods of analysis of the constructive elements were chosen so as not to damage or affect the violins in any way.

2.2. Methods

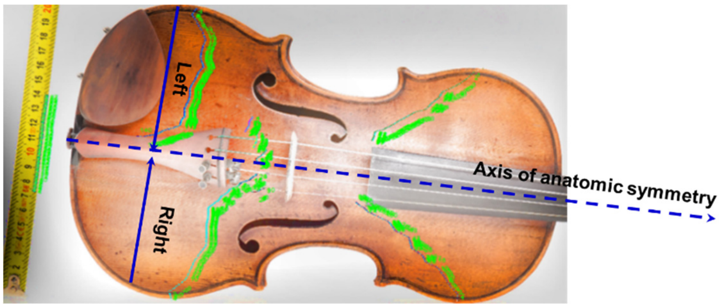
2.2.1. Anatomical Models of the Wood Structure

The determination of the anatomical models of the wood structure in the construction of the violins was made by analyzing their top and back plates, determining the characteristics of the annual rings in terms of their width (marked as TRW), the width of the early wood (EWW), the width of the late wood (LWW), and the wavelength of the curled fiber in maple wood (CWL wavelength), according to the methods presented in previous studies [21,22]. For the spruce plates, the width of early wood and late wood was measured along the entire maximum width of the boards, the coating with varnish and the anatomical structure of the wood, making it possible to gather these data. For the maple boards used in the construction of the back of the violin, only the width of the annual rings and wavelength of the curly fibers were measured in accordance with [41–43] (Figure 3). By analyzing the anatomical models of wood from the construction of old violins, it is possible to date and even locate the source of origin of the tree from which the wood was harvested, by reporting the measurements to an international database [40–43]. The technique is known as dendrochronology and is based on measuring and verifying the series of rings that have been cross-dated with each other with the WinDENDRO Density 2007 image-analysis system (WinDENDRO 2007), adopting a threshold of 0.60 as Gleichläufigkeit correlation coefficient [44].

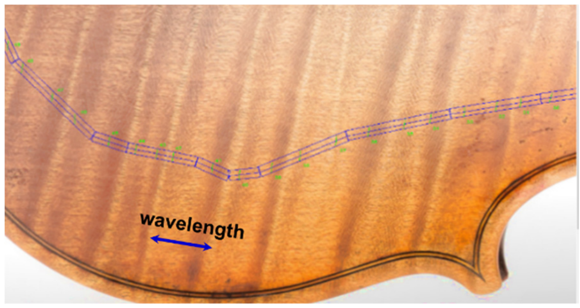
Figure 2. The studied violins.

2.2.2. The Dynamic Method

The study method started from the procedure used by old luthiers to hit the violin plate, listen to the sound produced by it and determine if further processing is needed [35]. Thus, the test method used in this research consisted of dynamic analysis to determine the frequency response of old violins compared to new violins. The structural excitation consists of hitting the body of the violin with the impact hammer (Figure 4a). In the first stage, the modal response of the structure was evaluated by hitting the body of the violin at different points on the surface. Finding that the frequency response is approximately identical in terms of resonant frequencies, regardless of the place of excitation, it was established that the point of hitting the violin should be at a distance of 150 mm from the bridge foot, in the treble part of the violin.

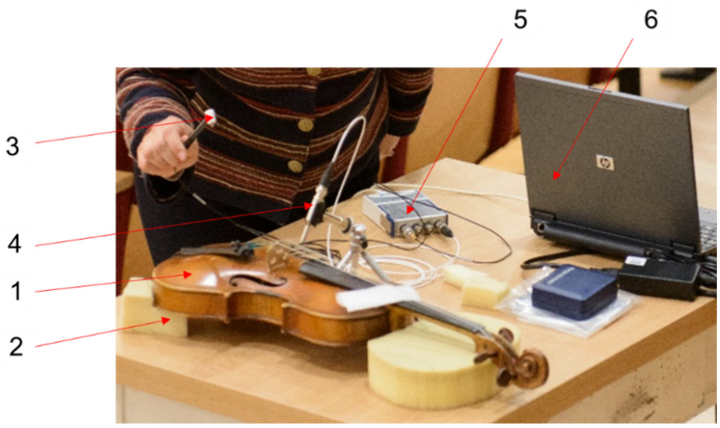


(a)



(b)

Figure 3. How to measure ring rings for the top plates/back plates of violins—case study of the Stradivarius Elder Voicu 1702 (photo courtesy of the "George Enescu" Bucharest Philharmonic and master violinist Tomescu Alexandru): (**a**) measuring the series of annual rings on the top plate; (**b**) measuring the wavelength of the curly fiber of maple from the back plate.



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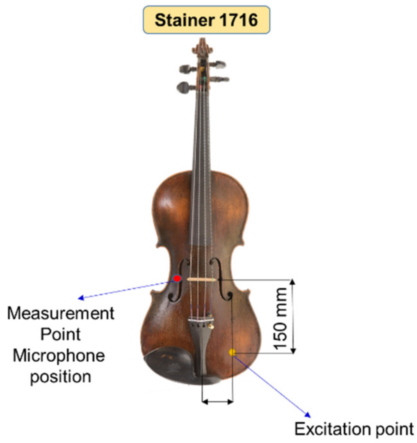


(b)

Figure 4. Violin testing: (**a**) excitation with the impact hammer; (**b**) the positions of excitation and measurement points. Legend: 1—tested violin; 2—elastic support; 3—impact hammer for light structures; 4—microphone; 5—data acquisition board; 6—laptop (software).

For this procedure, each violin was supported on elastic elements, thus simulating a free structure. Then, the violin body was excited using a B&K 8204 Brüel & Kjær (Nærum, Denmark) impact hammer, and the output signal was captured using a microphone type PCB 130E20 ICP (PCB Piezotronics, New York, NY, USA). In these investigations, the microphone was placed above the hole *f*, at a height of 150 mm, on the opposite side of the excited area. The recordings were performed in the same position with respect to the equipment and instrument (Figure 4b). The generated signals were transmitted via a signal conditioning device to a NI USB-9233 dynamic data acquisition board produced by National Instruments (Austin, TX, USA), connected to a laptop. The signal was viewed using a special application developed in NI-LabVIEW©, and the graphical data was processed using the MATLAB © program. Before each recording of the sounds emitted by the tested violin, the background noise from the test chamber was recorded. In the data processing stage, a noise filter was provided in the signal processing program, so that only the signals produced by the violin would result. The procedure has presented in previous research [17–19]. After the analysis of the time and frequency of the signals, based on the exponential curve of the damping and the spectral composition of the signal for each violin, the values of the specific frequencies of the tested violins, the quality factor and the analysis in time were extracted, these being correlated with aspects of wood structure and violin geometry. For each violin, the signals from two successive tests were taken. The quality factor Q is the ratio between the resonance frequency and the variation of the frequency at 0.707 times the amplitude of the forced vibration signal (1) [40,41].

$$Q = \frac{f_r}{f_{r2} - f_{r1}}, \tag{1}$$

where Q is the quality factor; f_r—the resonance frequency; f_{r1} and f_{r2} are two frequencies extracted at 0.707 from maximum amplitude related to resonance frequency. Based on relation (1), the quality factor Q of each analysed structure was determined from the time-frequency graph obtained experimentally. For each resonance frequency, the Q factor was calculated.

3. Results and Discussions

3.1. Symmetries in the Anatomical Structure of the Plates in the Construction of Old Violins

The macroscopic anatomical characteristics of the spruce and maple wood in the construction of the analyzed violins, presented as mean values and standard deviations, are centralized in Table 1. The spruce wood used for the Stradivarius Elder Voicu 1702 violin is characterized by very fine annual rings, with an average width of 0.672 mm. Average values under 1 mm wide are also found for new violins and the Copy Stainer violin. The highest proportions of late wood (over 37%) are found in the Stradivarius Elder Voicu 1702, Klotz 1747 and Gliga violins (Figure 5). Analyzing the structure of the maple wood of the back plate, it was observed that the violins with the narrowest annual rings are Stradivarius Elder Voicu 1702, Klotz 1747 and Babos 1920. In terms of the wavelength of the curly fiber, wavy fibers are found in new violins and old violins such as the Leeb 1742 and Stradivarius Elder Voicu 1702. It has been found that frequently strung and aged instruments show either degraded areas of wood and/or finish, or a pattern of wear due to varnish degradation after extensive manipulation and use by the violinist [30,34,35].

Table 1. Anatomical characteristics of spruce and maple wood on the front and back plates of the studied violins.

	Anatomical Characteristics—Mean (STDV)						
	Top Plate					Back Plate	
Studied Violins	**The Width of the Annual Rings (mm)**	**The Width of Early Wood (mm)**	**The Width of Late Wood (mm)**	**The Proportion of Early Wood (%)**	**The Proportion of Late Wood (%)**	**The Width of the Annual Rings (mm)**	**The Wavelength of the Curly Fiber (mm)**
Stradivarius 1702	0.672 (0.363)	0.432 (0.3)	0.242 (0.087)	60.787 (10.269)	39.213 (10.269)	1.081 (0.461)	5.754 (1.857)
Stainer 1716	2.247 (0.567)	1.676 (0.518)	0.496 (0.178)	76.184 (9.152)	23.816 (9.152)	1.908 (0.531)	4.021 (1.577)
Leeb 1742	1.53 (0.49)	1.148 (0.467)	0.382 (0.122)	73.564 (8.507)	26.436 (8.507)	1.246 (0.658)	6.421 (2.422)
Klotz 1747	1.251 (0.403)	0.792 (0.304)	0.459 (0.162)	62.635 (8.7)	37.365 (8.7)	1.063 (0.902)	NA
Babos 1920	1.891 (0.612)	1.449 (0.601)	0.442 (0.158)	74.379 (9.942)	25.203 (9.942)	1.026 (0.527)	3.946 (1.256)
Copy Stainer	0.985 (0.527)	0.689 (0.45)	0.3 (0.118)	66.127 (11.286)	33.873 (11.286)	1.277 (0.297)	4.984 (1.589)
Unbranded	1.327 (0.336)	0.907 (0.293)	0.42 (0.13)	67.689 (8.921)	32.311 (8.921)	4.563 (1.105)	4.585 (1.057)
Gliga 1, 2020	0.94 (0.234)	0.568 (0.19)	0.372 (0.1)	59.766 (8.388)	40.234 (8.388)	1.623 (0.666)	6.731 (3.371)
Gliga 2	0.977 (0.238)	0.606 (0.190)	0.370 (0.101)	61.549 (8.146)	38.450 (8.146)	1.389 (0.734)	4.271 (1.960)
Gliga 3	1.015 (0.323)	0.597 (0.227)	0.422 (0.145)	58.055 (9.293)	41.944 (9.293)	2.379 (0.935)	5.397 (2.342)

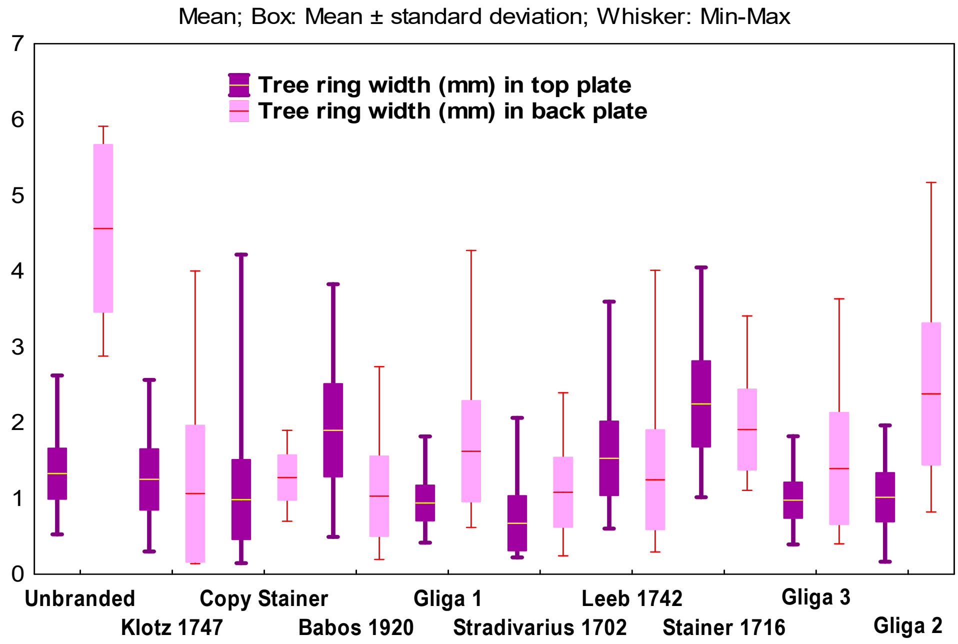


Figure 5. The variation of the annual ring width of the top and back plates of the analyzed violins.

The analyzed violins differ from each other at a very significant level in terms of all their structural characteristics, so each violin has its structural personality, which is presented below. Table 2 summarizes the values of the indicators for characterizing the symmetry of the halves of the violin faces, based on the detected degree of anatomical symmetry of the spruce plates. The Stradivarius Elder Voicu 1702 and Klotz 1747 violins show the highest result (Gleichläufigkeit correlation coefficient 65%).

Table 2. Indicators for characterizing the symmetry of the top halves in relation to the annual rings (* inaccessible for the measurement all annual rings in that half).

Violin	The Number of Rings		Gleichläufigkeit Correlation Coefficient (%)
	Right R	Left L	
Stradivarius Elder-Voicu 1702	94 *	167	65.1
Stainer 1716	38	42	62.7
Leeb 1742	67	52	61.3
Klotz 1747	59	68	65.8
Babos 1920	46	58	57.4
Stainer Copy	102	97	60.6
Unbranded	74	70	63.2
Gliga 1, 2020	110	106	61.5
Gliga 2	91	95	63.1
Gliga 3	97	98	60.7

The structural symmetry of the violin top plate, which is shown in Figure 6, was also investigated. It is found that the face board has the highest structural symmetry in the case of the Klotz 1747 violin, the unbranded violin, the Copy Stainer violin and the new violins. The other violins, Stradivarius 1702, Stainer 1716, Leeb 1742 and Babos 1920, show variations in the width of the annual rings, but the tendency to vary from one year to another has the same curve.

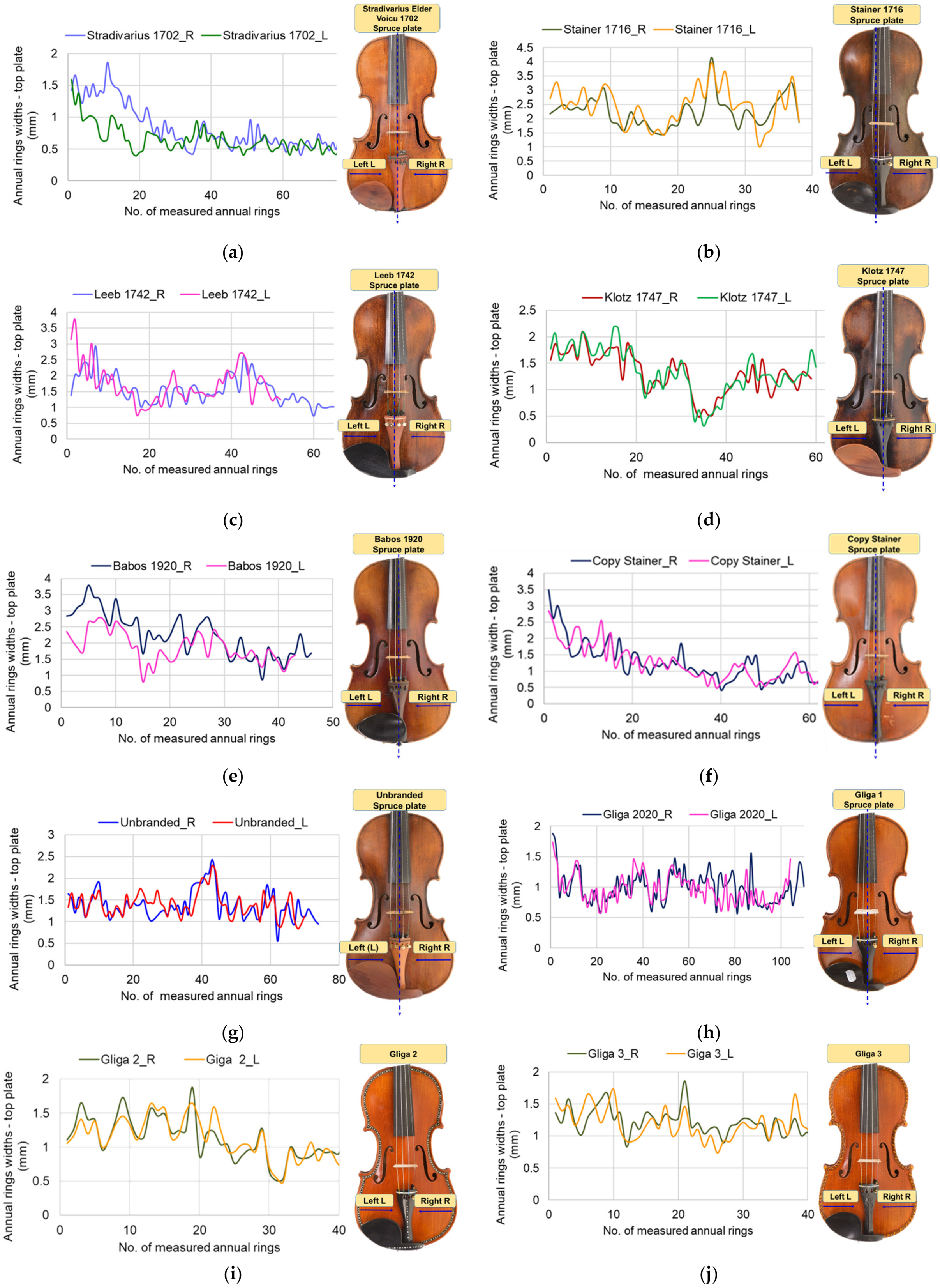
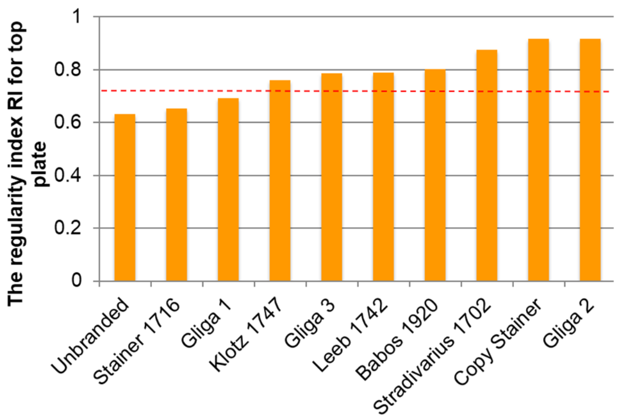


Figure 6. Analysis of the symmetry of the anatomical structure of spruce wood in the construction of violin top plate made from resonant spruce: (**a**) Stradivarius Elder Voicu 1702 violin; (**b**) Stainer 1716 violin; (**c**) Leeb 1742 violin; (**d**) Klotz 1747 violin; (**e**) Babos 1920 violin; (**f**) Copy Stainer violin; (**g**) Unbranded violin; (**h**) Gliga 1, 2020 violin; (**i**) Gliga 2 violin; (**j**) Gliga 3 violin.

However, the results presented are subject to the inaccessibility for measuring purposes of some rings due to the finishes, the accessories on the violin and the constructional shape of the instruments (which, as stated, are still functional, used by their owners and cannot be destroyed). The Babos 1920 violin has the lowest value of degree of symmetry among the analyzed violins, but still over 50%. For the Klotz 1747, Babos 1920, Leeb 1942, and Stainer 1716 violins, the rings in the back structure are considerably finer than those in the top plate structure, while for the violins Unbranded, Stradivarius 1702 and all new violins, the spruce rings from the top plates are much finer than those of the back. In 40% of cases, the regularity index of the width of the RI rings is within the limits specified by Rocaboy and Bucur (1990) [45] for resonant wood (RI $\leq$ 0.700). For most violins, there are big differences between front and back regarding the regularity of the rings. The rings of the top are usually more regular than those of the back (Figure 7). On average, late wood has a third, and early wood the other two-thirds of the annual ring width. The proportions of the two components of the annual rings show a moderate level of variability (coefficient of variation: 16% and 32%, respectively). At 76% of the recorded values of the proportion of late wood, there is an exceedance of the reference level of 25% mentioned for the resonant spruce [46].



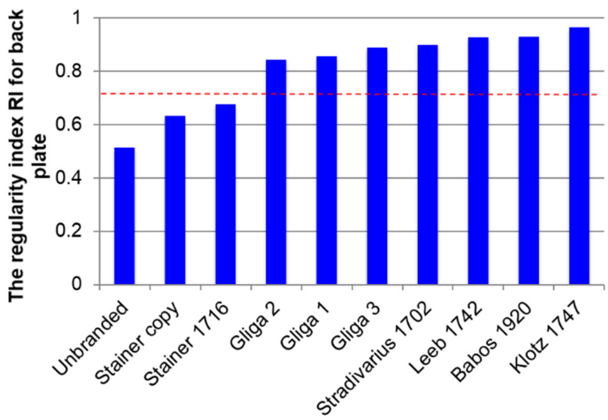


Figure 7. Variation of the regularity index: (**a**) for spruce wood from top plates; (**b**) for maple wood from back plates of studied violins.

There are violins in which the central tendency of the late wood increases to 40% of the width of the ring. It is not excluded that this result may be influenced by the finishing techniques of the violin, which would have led to an overestimation of the width of the late wood in the imaging analysis. Regarding the anatomical structure of the back plates, made of curly maple fiber, it was observed that, for the Unbranded and Klotz 1747 violins, the back plate is obtained from a single curled maple wood piece, compared to the other analyzed violins in which the back consists of two semi-finished products glued on the axis of longitudinal symmetry. Specific to the curly maple is the distance between the tips of the fiber ripples, known as the wavelength of the fiber, which gravitates at around 4.4 mm. The smallest value (1.35 mm) was measured on the Stainer 1716 violin, and the highest (13.11 mm) on all the new violins. The differences between the violins are noticeable, some having tight curly fiber, others wide curly fiber. There is a tendency to associate the wavelength with certain values of the annual ring width, i.e., the dense curly fiber appears especially in maple wood with wider rings (Spearman rank correlation coefficient $R = -0.156$, $p = 0.04$).

3.2. Dynamic Analysis

The dynamic test of the violins with the impact hammer resulted both in the time damping graphs of the signal and in their frequency analysis. For each violin, two tests were performed and the type of graph obtained is shown in Figure 8. It can be seen that the modal response of violins fluctuates from one violin to another, but in the low frequency range (signature mode) they are very distinct—with peaks and troughs, these aspects being highlighted by [3,6,9,11,34,38] even if the method of exciting the violin body was different. For each violin, the violin-specific eigenvalues were extracted (the first five values) which were then analyzed comparatively (Table 3).

Table 3. Eigenvalues for the first vibration modes of old versus new violins.

Violins	The Frequency Spectrum (Hz) AVERAGE/STDV				
	f1 (A0)	**f2 (CBR)**	**f3 (B1−)**	**f4 (B1+)**	**f5**
		Stainer 1716			
Frequency (Hz)	283.55 (1.77)	389.70 (0.28)	449.50 (0.42)	604.95 (2.33)	857.00 (0.0)
Quality factor Q	11.94 (2.03)	14.32 (0.00)	30.08 (2.03)	22.28 (2.25)	77.99 (0.90)
		Leeb 1742			
Frequency (Hz)	282.30 (0.00)	415.80 (0.00)	470.70 (0.00)	561.50 (0.00)	685.85 (1.06)
Quality factor Q	17.35 (0.68)	24.99 (0.23)	20.69 (0.00)	21.65 (0.45)	24.83 (0.90)
		Klotz 1747			
Frequency (Hz)	290.65 (1.06)	429.50 (0.00)	481.05 (0.49)	572.30 (0.14)	681.70 (0.57)
Quality factor Q	21.96 (2.25)	51.09 (2.48)	23.87 (0.45)	44.40 (1.58)	17.19 (1.80)
		Babos 1920			
Frequency (Hz)	288.00 (2.69)	-	489.40 (0.57)	535.20 (0.57)	661.70 (0.42)
Quality factor Q	14.32 (0.45)	-	26.42 (1.35)	42.34 (4.95)	27.69 (4.05)
		Copy Stainer			
Frequency (Hz)	294.20 (0.00)	389.75 (0.07)	458.65 (2.06)	544.30 (3.82)	823.35 (0.49)
Quality factor Q	7.64 (0.00)	43.77 (0.68)	32.63 (0.68)	33.42 (0.45)	30.08 (0.23)
		Unbranded			
Frequency (Hz)	275.75 (0.49)	409.70 (0.00)	479.85 (0.07)	536.70 (0.57)	838.20 (0.28)
Quality factor Q	15.28 (1.80)	49.66 (4.50)	26.10 (6.30)	22.44 (1.13)	37.40 (6.53)
		Gliga 1, 2020			
Frequency (Hz)	273.10 (0.00)	399.40 (0.57)	473.80 (0.00)	-	688.10 (0.00)
Quality factor Q	25.46 (0.00)	37.56 (3.60)	20.37 (0.45)	-	51.88 (0.00)
		Gliga 2			
Frequency (Hz)	275.00 (0.00)	407.00 (0.00)	430.00 (0.00)	523.50 (0.71)	675.00 (33.94)
Quality factor Q	21.33 (1.35)	21.65 (0.90)	33.58 (0.68)	26.26 (0.23)	28.01 (0.45)
		Gliga 3			
Frequency (Hz)	274.50 (0.71)	440.50 (0.71)	476.50 (19.09)	530.20 (6.79)	664.50 (31.82)
Quality factor Q	17.19 (0.00)	35.65 (3.60)	28.01 (0.90)	24.19 (4.95)	31.51 (0.45)

The quality factor was calculated based on the data extracted from the frequency analysis for each value, as can be seen in Table 3. The comparison of eigenvalues for the cavity modes and corpus bending modes are presented in Figure 9. The lowest natural frequency is recorded in the case of new violins and the highest fundamental frequency is presented in the Babos 1920, Klotz 1747 and Copy Stainer violins. The first mode is the A0 mode, known as the vibration mode of the air in the violin body. In the case of mode 2, at around the frequency of 400 Hz, the rhomboidal vibration mode is formed (known in the literature [6–9] as the CBR mode). Thus, the closest values of the CBR mode frequency are recorded for the Stainer 1716 violin and copy Stainer (frequency 389 Hz in both cases). The Gliga 1 violin recorded a frequency of 399 Hz which is almost equal to the specific CBR frequency. For the other violins, the CBR mode has higher values, ranging between 410–440 Hz as can be seen in Figure 9b. For the next resonance mode (B1−), the eigenvalues are in the range 430 Hz–490 Hz, the lowest value of 430 Hz presented by the Gliga 2 violin, followed by the Stainer copy violin (460 Hz). The Leeb 1742, Gliga 1, Gliga 3, Unbranded, Klotz 1747 and Babos 1920 violins recorded very close values of (B1−) modes (Figure 9c).

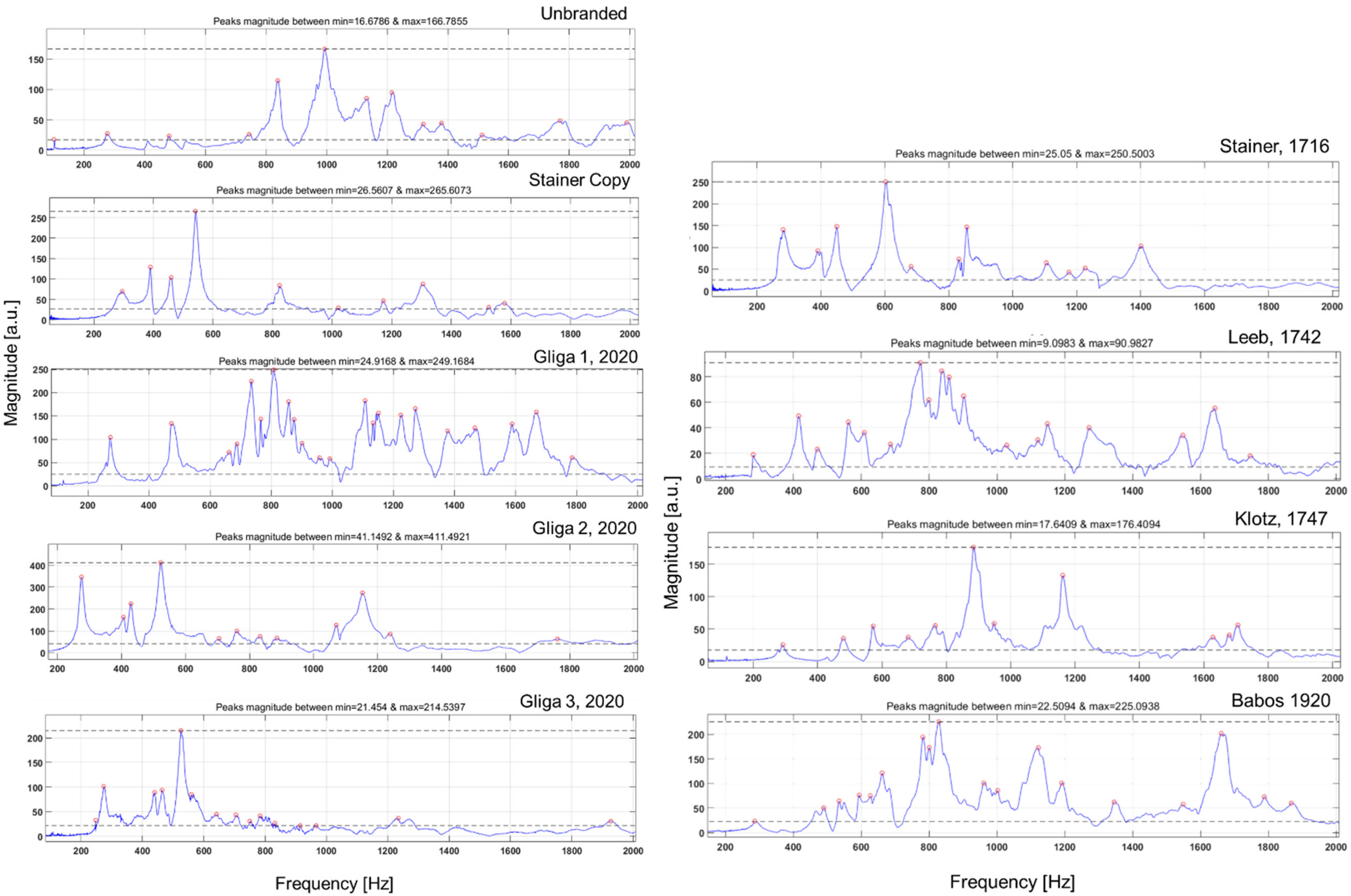


Figure 8. The frequency spectrum plots for the dynamic analysis.

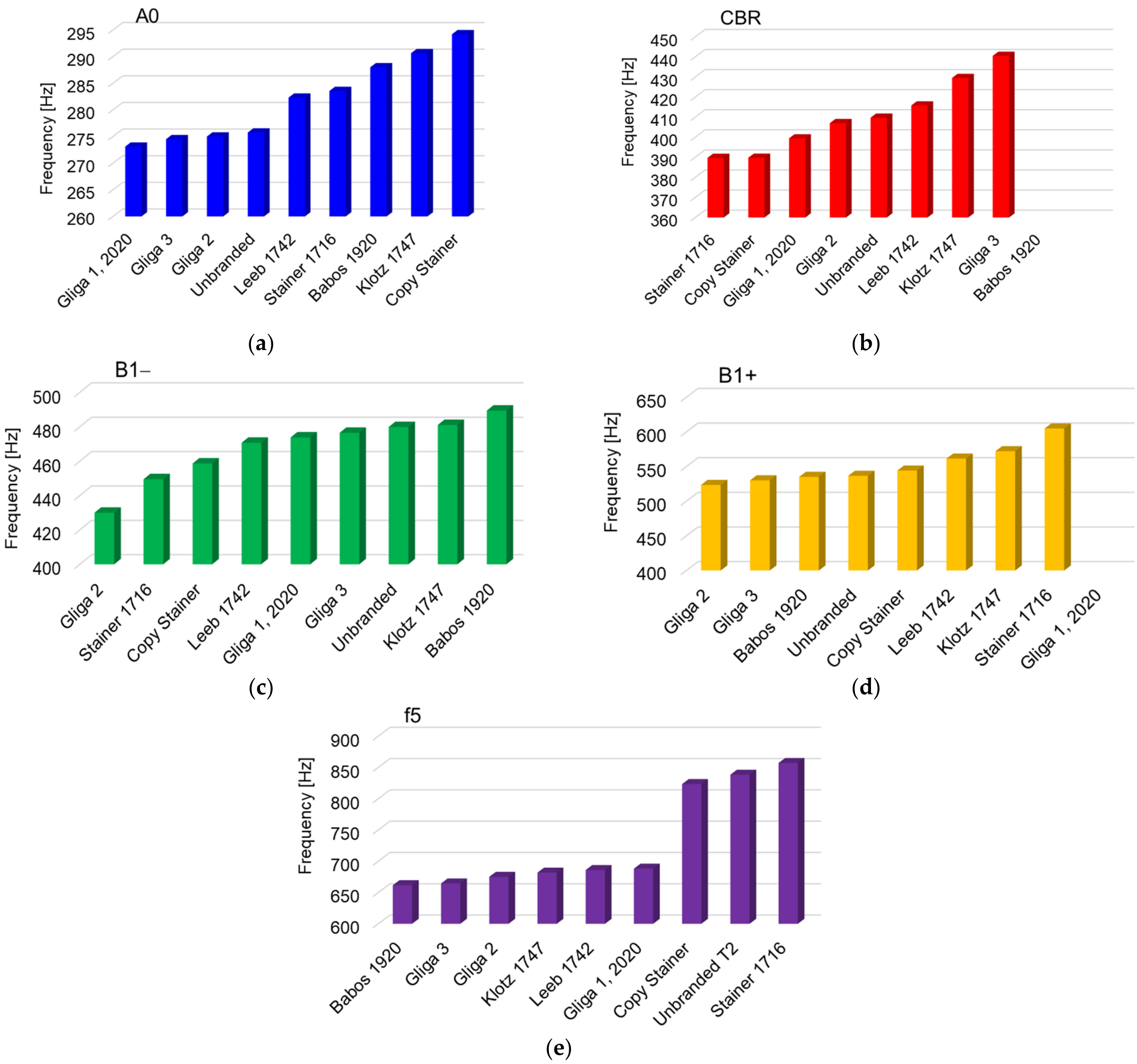


Figure 9. Comparisons between the values of the natural frequencies of the tested violins: (**a**) cavity mode; (**b**) CBR mode; (**c**) B1− mode; (**d**) B1+ mode; (**e**) the 5th resonance frequency.

In the case of the B1+ bending mode, the eigenvalues are between 523 Hz and 604 Hz, as can be seen in Figure 9d. The only violin that does not have this harmonica is the Gliga 1 2020 violin. The Leeb, Klotz and Stainer violins show close values of B1+ mode, ranging from 550 to 600 Hz. According to [11,24,47], violins with a frequency of B1+ less than 510 Hz are characterized by a soft, dark sound, and those with a frequency greater than 550 Hz have a bright to harsh sound. Thus, the Babos 1920, Unbranded, Copy Stainer, Gliga 2 and Gliga 3 violins record a frequency of the B1+ mode in the range 510–550 Hz, while Stainer 1716, Leeb 1742, and Klotz 1747 have a frequency value over 550 Hz, according to [11,24,47,48]. In the case of mode 5, there is a division into two groups of values: Babos violins, all new violins, Klotz 1747 and Leeb 1742 record a frequency in the range 660–690 Hz, compared to Stainer 1716 violins, Stainer copy and Unbranded that form the second group of values in the range 820–860 Hz (Figure 9e).

The Q quality factor defines the musical instrument's ability to dampen vibrations or how fast resonance will fade out after the system excitation has ceased. For each resonance frequency, the value of Q factor was determined as can be seen in Table 3. In Figure 10, the comparison between quality factors of the studied violins can be observed.

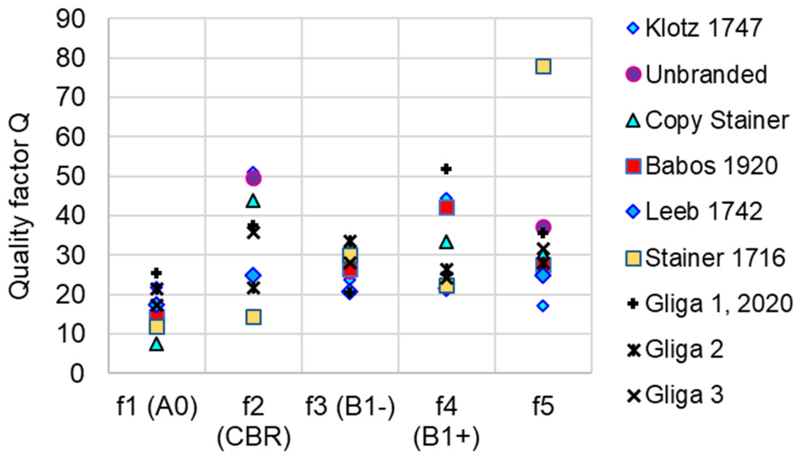


Figure 10. The quality factor variation.

The value of Q for the A0 resonance mode is the lowest, for all tested violins, ranging from 7 to 25, being in good accordance with [34–38], who report, as an average value for the violins tested, 14.5. In this study, the lowest value is recorded for the Copy Stainer and Stainer 1716. In early studies by [47], Saunders identified a value of 20 for Q for the main air resonance, A0, in the case of old Italian violins. Compared to this value reported by [47], in the present study, Klotz 1747 and Gliga 2 violins have a Q-factor of 21.

For B1− and B1+ modes, [37] reports Q-factor values of 32 (B1−) and 40 (B1+), respectively. In this study, for the B1− mode, the Stainer 1716 violins, the Stainer copy and the Gliga 2 register a quality factor of 30, 32 and 33, respectively, and the other violins have a lower Q-factor, of between 20–28. For the B1+ mode, the Klotz 1747 and Babos 1920 violins show values of the quality factor close to the value reported by [37], while the other violins fall within lower values.

3.3. Correlation between Symmetries of Wood Anatomical Structure and Signature Modes

The contribution of the symmetry of the face halves and the wavelength of the wavy fiber to the size variation of the dynamic parameters was examined using the coefficient of determination, calculated on the assumption of a linear relationship between variables. Table 4 summarizes the correlations between the Gleichläufigkeit correlation coefficient between the series of rings in the right and left halves of the front plate of the violins, the wavelength of the corrugated fiber in the structure of the back plate and the determined dynamic parameters. The size of the quality factor Q5 is inversely proportional to the regularity index RI; for instance, the violins with the best regularity of the rings on the face have a higher quality factor Q5 (RI actually expresses the irregularity of the rings). From the point of view of the correlation of the frequency response with the anatomical structure of the wood, it was observed that the symmetry of the face construction intervenes most on the values of specific frequencies specific to CBR, B1+, and f_5 modes that increase with the improvement of top plate symmetry. The wavelength of the curly fiber specific to maple wood in the composition of the back of the violins makes a modest contribution in terms of frequency spectrum, with a slightly sensitive influence on the first two modes of vibration (A0 and CBR). Thus, it was found that the value of the frequency f_1 decreases, and that of the frequency f_2 increases with the wavelength of the fiber.

Table 4. Correlation between anatomical structure of wood (from top and back plates) and dynamic parameters.

Dynamic Parameters	Coefficient of Determination (R2,%) in Relation to:		
	Top Plate Symmetry *	Regularity of Annual Rings from Top Plate	Wavelength of Curly Fibres of Maple
f1 (A0)	0.84	11.27	9.48
f2 (CBR)	33.21	0	0.67
f3 (B1−)	0.29	15.05	1.15
f4 (B1+)	0.93	0.31	10.22
f5	0.12	2.11	4.02
Q (f1 (A0))	7.81	2.31	38.64
Q (f2 (CBR))	21.55	0.56	0.06
Q (f3 (B1−))	2.92	23.03	28.11
Q4 (f4 (B1+))	1.29	0	9.53
Q5 (f5)	0.27	27.48	14.7

* is expressed by the Gleichläufigkeit correlation coefficient between the series of rings in the right and left half of the top plate of the instrument.

4. Conclusions

An experimental investigation was performed on ancient and modern violins in order to determine the correlation between anatomical structure of the wood from top and back plates and the signature modes of the violins. The most important findings consist of identification of the first five modes for old violins, (known as provenance), current new violins, and violins whose origin is unknown, but which could correlate with anatomical, constructive and dynamic characteristics to be able to establish origins, and the measurement of the anatomical features of top and back plates from the violins' construction. The results are consistent with the results reported in the literature, but moreover they emphasize the vibrational properties for each historical and newly studied violin. On the other hand, another test method is proposed, different from the one presented in the literature, but which offers similar results to those reported by other methods, in terms of the response of violin structures to modal excitation.

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