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ORIGINAL ARTICLE

Effect of wood species on vibration modes of violins plates

Mariana Domnica Stanciu[1] · **Camelia Coşereanu**[2] · **Florin Dinulică**[3] · **Voichița Bucur**[4]

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Abstract

The aim of this article is to correlate the experimental modal analysis (EMA) with finite element analysis (FEA) to study the effect of wood species on vibration modes of violin plates made of spruce and maple. For EMA, five violin plates each made of spruce and maple were tested (curly maple, quilted maple, common maple with regular and irregular rings). The plates were clamped on edges and subjected to forced vibration. Experimental Chladni patterns of these plates were determined for 36 emitted frequencies, range between 65 and 2637 Hz. Patterns obtained with modal analysis are characterised by the nodal lines. The patterns of vibration modes are affected by wood species and structure. Spruce plate shows nodal lines aligned to the longitudinal (L) anisotropic direction of wood, corresponding to the direction of the fibres. Maple plates show nodal lines aligned to radial (R) anisotropic direction of wood and to the direction of medullary rays in the LR plane. Curly maple plate vibration produced the best resolution of vibration modes pattern, because of the presence of very abundant medullary rays, well oriented in the R direction. Quilted maple plate has asymmetric modes of vibration. At the highest frequency of 2093 Hz, no vibrating zones were observed during the experiment. Maple plates of normal structure with regular and irregular annual rings have shown similar patterns, but differ from curly maple plate. The characteristics of annual rings were measured. The vibrating surfaces (S_v) of the plates obtained experimentally were measured by transferring the nodal lines into AutoCAD 2013 software, where the surfaces were computed and expressed in mm^2 or in % of the total surface area of the plate; the total effective vibrating surface for all frequencies for each plate and wood species; the relative vibrating surface at maximum amplitude. The experimental results were compared to modal analysis performed with FEA, by using ABAQUS program. The similar geometry of the real plates was generated in ABAQUS and the violin plates were meshed with quadratic shell elements. The plates were modelled as orthotropic materials. At maximum vibration amplitude and frequency of 110 Hz, the spruce plate has a relative vibrating surface of 62%, a mean annual ring width of 0.77 mm and ring heterogeneity of only 64%. At maximum amplitude of vibration and frequency of 174 Hz, the plates made of curly maple LR and LT (longitudinal–tangential), have different behaviour. The vibrating surface is greater for the plate made of curly maple LR with dense figures (84%) and annual ring heterogeneity of 86%, than for plates made of curly maple LT with large figures (77%) and annual ring heterogeneity of 238%.

1 Introduction

It is known that spruce is used for the top plate of the violin and curly maple is preferred by many luthiers for their violin back plate (Hutchins 1981). Spruce (*Picea abies*) for the top plate, also called spruce resonance wood or tone wood, and curly maple (*Acer pseudoplatanus*) of typical anatomical structure, for the back plate, have been traditionally used for violins since the Baroque era. Acoustical and mechanical parameters of these species have been widely presented in reference books (Bucur 2006a, 2016) and articles (Obataya et al. 2000; Buksnowitz et al. 2007; Stanciu et al. 2008; Brémaud 2012; Carlier et al. 2019). Violin plates should be quarter sawn, in the longitudinal-radial

✉ Mariana Domnica Stanciu
mariana.stanciu@unitbv.ro

[1] Department of Mechanical Engineering, Transilvania University of Brasov, Faculty of Mechanical Engineering, Eroilor 29, 500036 Brasov, Romania

[2] Department of Wood Processing and Wood Products Design, Faculty of Wood Engineering, Transilvania University of Brasov, Eroilor 29, 500036 Brasov, Romania

[3] Department of Forest Engineering, Forest Management and Terrestrial Measurements, Transilvania University of Brașov, Faculty of Silviculture and Forest Engineering, Șirul Beethoven 1, 500123 Brasov, Romania

[4] RMIT University, School of Science, GPO Box 2476, Melbourne, VIC 3001, Australia

(LR) anisotropic plane of wood. However, some famous violins made for example by Guarneri, have the back plate in curly maple, flat sawn—in the longitudinal–tangential (LT) anisotropic plane of wood. The acoustic parameters in terms of modal radiation and signature modes of heritage and new violins (no. 17) were analysed by Bissinger (2008), who noticed that the old Italian violin recorded higher radiation and total damping in comparison with the others. The mechanical and acoustical properties of wavy maple and the correlation between density and elasticity modulus were investigated by Kudela and Kunstar (2011) and Sonderegger et al. (2013). An alternative wood species used for the back plate of musical instruments can be walnut and cherry. Their mechanical properties were studied by Bachtiar et al. (2017).

Gough (2007) investigated the vibration modes of freely supported and edge-constrained top and back plates according to shape, arching, thickness graduation, the effect of coupling on the ribs, etc. The most recent state of the art reference on violin acoustics was published in 2014 by Woodhouse (2014). In these articles, no reference is made to qualitative and quantitative vibration surface of the violin plates.

Yu et al. (2010) approached the optimization problems of violin plate's thickness in accordance with nodal lines, starting from a uniform thickness of plates and then varying the plate thickness until the minimum displacement of nodes along the nodal lines was obtained. Lu (2013) analysed the vibrational patterns of violin top plates using the numerical simulation and experimental tests based on operational modal analysis (OMA). For OMA, Lu (2013) applied free boundary conditions of violin top plates made from spruce and composite material. For experimental set-up, he used an impact hammer as excitation force and the signals were measured by means of accelerometer.

The aim of this article is to use FEA to study the effect of wood species on the vibration modes of violin plates. The vibrating surfaces of the plates were measured by transferring the nodal lines into AutoCAD 2013 software, where the surfaces were computed and expressed in mm^2 or in % of the total surface of the plate. The relative vibrating surface at maximum amplitude was also recorded. For experimental determination of the vibrating surface of violin plates, five violin plates made of spruce and maple (curly maple, quilted maple, maple) of normal structure with regular and irregular annual rings were tested. Experimental Chladni patterns on edge pinned plates were compared with FEA vibration patterns (36 emitted frequencies, between 65 and 2637 Hz).

2 Materials and methods

2.1 Material

2.1.1 Plates and wood species

The following wood species were selected: for the top plate of the violin, spruce (*Picea abies* L) and for the back plate of the violin, maple (*Acer pseudoplatanus* L). Spruce wood has small regular annual rings. Maple wood was chosen with four options, such as curly maple with a small wavy pattern and curly maple with a large wavy pattern, common maple with small and regular annual rings, and common maple with small and irregular annual rings. For experimental tests, five plates (one from resonance spruce (denoted S) and four from maple (denoted M)) were cut quarter sawn, (LR plane). The features of the annual rings of spruce and maple were determined by means of density image-analysis system, which is described in Sect. 2.2.2. Based on the method of grain angle measurement presented by Alkadri et al. (2018), the back plate made from maple with different grain figures was graded into four classes: curly maple with small wavy patterns (denoted QM), curly maple with large wavy patterns (denoted CM), common maple with small and regular rings (denoted DUM) and common maple with small and irregular annual rings (denoted NUM) (Fig. 1). This morphological particularity is a "defect" of the wood structure consisting of reaction wood formation and having aesthetical value for wood used for musical instruments or fine furniture (Ewald and Naujoks 2015). Relationships between anatomical features, elastic and vibrational properties of sycamore maple are explained by Kudela and Kunstar (2011), Sonderegger et al. (2013) and Alkadri et al. (2018). SEM images of the submicroscopic structure of curly maple are described in Bucur (1992).

2.1.2 Annual ring characteristics

The main parameter of macroscopic wood structure is the annual ring width. In this study, the width of the annual rings was measured on plates using WinDENDRO density image-analysis system (Régent Instruments 2007), with accuracy of 0.001 mm. Samples were scanned at 2200 dpi resolution. A series of 30 rings was measured for each plate. The annual rings are characterised by the following parameters (Bucur 2006b; Dinulica et al. 2019):

- width of annual ring (denoted W): mean (denoted W_{Mean}), most probable value (MPV) is the value that appears most often (according to statistical definition,

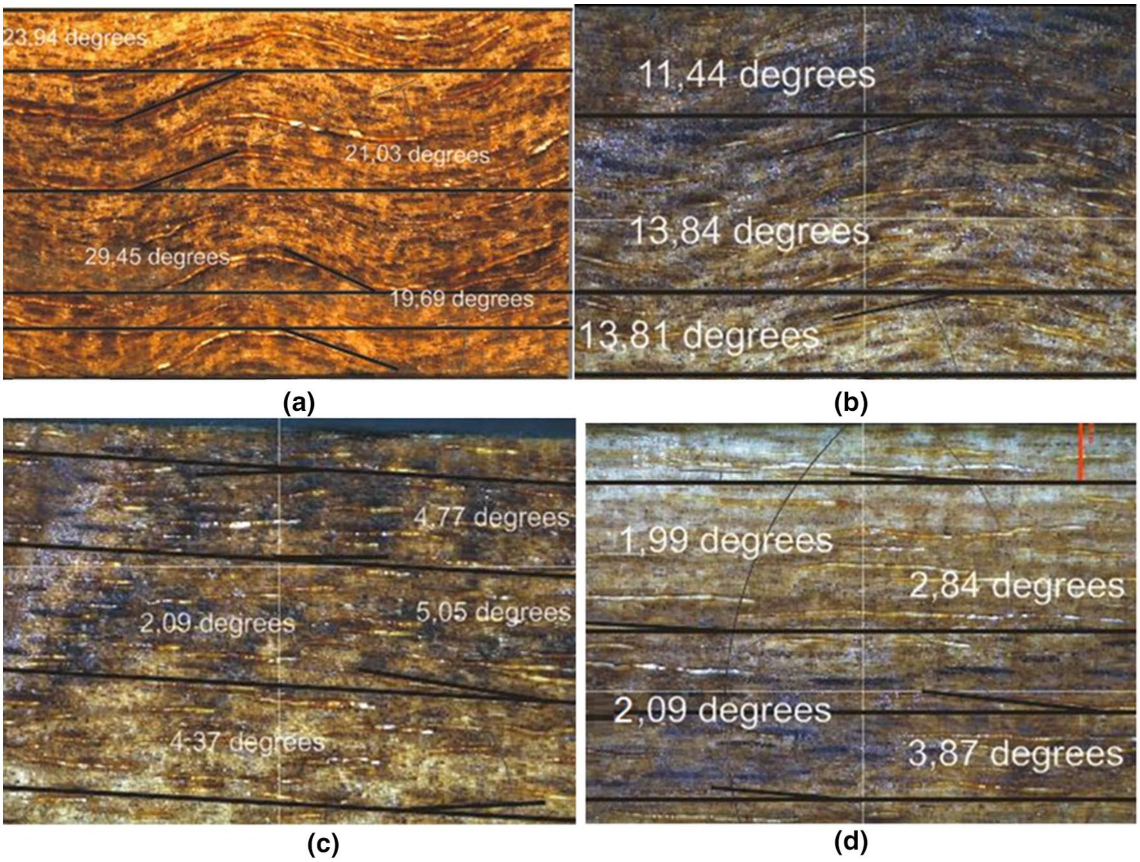


Fig. 1 Measurement of grain angle of maple violin plates: **a** curly maple with small wavy patterns (denoted QM); **b** curly maple with large wavy patterns (denoted CM), **c** common maple with small and regular rings (denoted DUM); **d** common maple with small and irregular annual rings (denoted NUM)

the MPV of a density function is supposed to mean the point in which the most mass is located, according to Gujarati 2006); minimum (W_{Min}) and maximum width (W_{Max});

- standard deviation is a measure of the statistical dispersion of the width of annual rings;
- coefficient of variability explains the variability of the annual rings in relation to the mean of all annual rings measured;
- the most probable value of width is related to maximum number of annual rings deduced from the frequency distribution;
- Pearson's asymmetry index (A) for the series of analysed annual rings. This index could be negative or positive, depending on the growth conditions of trees or other factors. Data in forest biometry very often show negative asymmetry, determined by specific growth conditions of trees. (A) is calculated as A = (Mean − Most probable value)/coefficient of variation;
- Regularity gives the amplitude of variation of the annual ring width. The regularity of annual ring width (R) is calculated from the maximum and minimum annual ring widths. Regularity $R = (W_{Max} - W_{Min})/W_{Max}$ (%);
- Heterogeneity takes into consideration W_{Max}, W_{Min} and W_{Mean}, and is calculated as $HT = (W_{Max} - W_{Mean})/(W_{Mean} - W_{Min})$.

2.2 Methods

2.2.1 Experimental modal analysis of plates

Experimental modal analysis requires the excitation of a violin plate with a loudspeaker cone driven by a sine wave oscillator. The plates were pinned on the edges. When the frequency of the sound from the loudspeaker strongly excites a resonance mode, the fine sand on the plate, moves to the nodal line positions of the vibrating plate. The scheme of the experimental devices with a loudspeaker is shown in Fig. 2a. Using the sound generator (6), the non-contact vibration source with amplifier (4) excites the sample (1), which is clamped in the device (3). The plates can support longitudinal, flexural and torsional modes of vibration. The stationary waves of the plate vibrate the

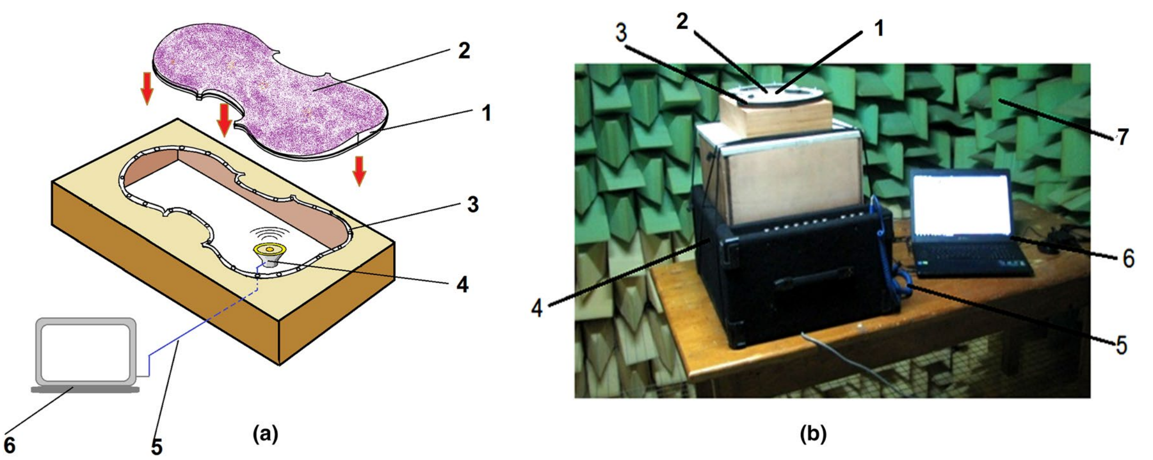


Fig. 2 Experimental devices: **a** The principle of the vibration generator during the tests. **b** Experimental set-up in anechoic chamber. 1—sample (tested plate); 2—sand spread evenly over the surface of the tested plate; 3—boundary condition (clamped edges of plate); 4—non contact vibration source with amplifier; 5—connectors; 6—sound generator; 7—anechoic chamber

sand grain, which will move to the nodal line known as Chladni patterns. The tests were performed in anechoic chamber from S. C. Hora S. A Reghin, Romania as can be seen in Fig. 2b.

2.2.2 Finite element analysis of plates

Finite element analysis (FEA) was used to study the effect of wood anisotropy on violin plates made of spruce and maple.

The anisotropy depends on the internal structure of the material. Wood has three natural axes of symmetry, L, R and T, and three mutually planes of symmetry which allow us to accept the hypothesis of orthotropic elastic symmetry for this material. The response of wood to an applied stress depends on its elastic symmetry (Bodig and Jayne 1982). The number of constants for various types of anisotropic materials is 21 for monoclinic materials, 13 for triclinic materials, 9 for orthotropic materials, 5 for hexagonal or transversely isotropic materials and 2 for isotropic materials (Bucur 2006a). In case of wood, when the axes are labelled L, R and T for wood species as can be seen in Fig. 3, the engineering constants are related to the compliances (C) in the following form (1):

$$\begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{LR}}{E_R} & -\frac{\nu_{LT}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{RL}}{E_L} & \frac{1}{E_R} & -\frac{\nu_{RT}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{TL}}{E_L} & -\frac{\nu_{TR}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} = [C]. \tag{1}$$

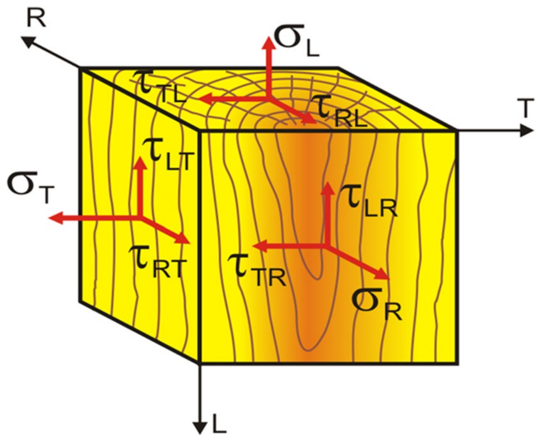


Fig. 3 Main planes and axis of elastic symmetry of wood

In case of wood, the stress and strain states of wood pieces are represented by stress tensor and strain tensor (2), respectively (Kats et al. 2008; Bremaud et al. 2011):

$$T_\sigma = \begin{pmatrix} \sigma_L & \tau_{RL} & \tau_{TL} \\ \tau_{RL} & \sigma_R & \tau_{RT} \\ \tau_{TL} & \tau_{TR} & \sigma_T \end{pmatrix}; \quad T_\varepsilon = \begin{pmatrix} \varepsilon_L & \frac{1}{2}\gamma_{LR} & \frac{1}{2}\gamma_{LT} \\ \frac{1}{2}\gamma_{LR} & \varepsilon_R & \frac{1}{2}\gamma_{RT} \\ \frac{1}{2}\gamma_{TL} & \frac{1}{2}\gamma_{TR} & \varepsilon_T \end{pmatrix}, \tag{2}$$

where σ_L, σ_R, *şi*, σ_T are normal stresses in longitudinal (L), radial (R) and tangential (T) direction; τ_{LR}, σ_{RT}, *şi*, τ_{LT}—tangential stresses in planes LR, RT şi LT; ε_L, ε_R şi ε_T—strains; and γ_{LR}, γ_{RT}, *şi*, γ_{LT}—shearing strain. Using the tensor of modulus of elasticity E and the tensor of Poisson coefficients, results in (3):

$$\begin{cases} \varepsilon_L = \frac{1}{E_L}\left(\sigma_L - \nu_{LR}\sigma_R - \nu_{LT}\sigma_T\right); \gamma_{TR} = \frac{\tau_{TR}}{G_{TR}}; \\ \varepsilon_L = \frac{1}{E_R}\left(\sigma_R - \nu_{RL}\sigma_L - \nu_{RT}\sigma_T\right); \gamma_{RL} = \frac{\tau_{RL}}{G_{RL}}; \\ \varepsilon_L = \frac{1}{E_T}\left(\sigma_T - \nu_{TL}\sigma_L - \nu_{TR}\sigma_R\right); \gamma_{LT} = \frac{\tau_{LT}}{G_{TL}}; \end{cases} \tag{3}$$

where $\nu_{LR}, \nu_{LT}, \nu_{RL} \dots$ are coefficients of transverse contraction (first index represents the direction of transverse contraction and the second, the direction of the stress which produces the elongation).

As noted by Hermon (1948), the longitudinal modulus E_L of a given specimen and moisture content represent the most significant elastic constants, which affect the mechanical and dynamical behaviour of wood. However, the modulus of rigidity depends on the experimental conditions. Hermon (1948) also noted that there is a consistent difference between dynamic and static methods of measuring these constants “none the less no regular change with frequency has been observed, even at the lowest frequency attainable” (ranging between 26 and 1300 Hz). In addition, no significant effect of frequency on the ultrasonic stiffness in the L direction, in the range 0.1–5 MHz, was reported by Bucur (2006a). Therefore, it can be noted that in the L anisotropic direction, wood is not a dispersive material. No data exists in the literature regarding the effect of frequency on Poisson ratio. The mechanical characteristics of wood are given in Table 1. The values from Table 1 are selected starting from values of Young’s moduli E and shear moduli G from references (Bucur 2006b; Szalai 1994). To obtain all engineering parameters for wood as orthotropic material, the ratios between the directions L:R:T accounting for 9.8:1.7:1 for Young’s moduli and of the shear moduli in the shearing planes LT:LR:RT accounting for 4.5:2.9:1 were applied in accordance with Sonderegger et al. (2013).

The finite element analysis of violin plates was performed by using ABAQUS software. Similar analysis taking into account the anisotropy of wood was performed by Lomte (2013). The plates have no f-holes and are flat with a constant thickness of 3 mm. The violin plate was meshed with a quadratic shell element (9495 finite elements), with eight nodes located in corners (total 28,664 nodes). Such an element is based on the theory of small and medium thick plates and can be used in the analysis of large deformations. The plates were edge-constrained as shown in Fig. 4a. Figure 4b shows the structural elements.

The dynamic response of the plate is obtained based on Kirchhoff’s hypotheses and applying the d’Alembert principle or another energy method, Eq. (4) (Lee et al. 2016; Stanciu et al. 2019):

$$\Delta\Delta \mathrm{w}(\mathrm{x}, \mathrm{y}, \mathrm{t}) + \frac{\rho h}{\mathrm{D}} \frac{\partial^2 \mathrm{w}(\mathrm{x}, \mathrm{y}, \mathrm{t})}{\partial \mathrm{t}^2} = \frac{\mathrm{p}(\mathrm{x}, \mathrm{y}, \mathrm{t})}{\mathrm{D}}, \tag{4}$$

where $\mathrm{w}(\mathrm{x}, \mathrm{y}, \mathrm{t})$ represent the normal instantaneous displacement on the median surface of the plate; $\mathrm{D} = \frac{\mathrm{Eh}^3}{12(1-\nu^2)}$—bending modulus of the plate, h—thickness of the plate, E—the modulus of elasticity and ν—Poisson’s coefficient; $\mathrm{p}(\mathrm{x}, \mathrm{y}, \mathrm{t})$—the distributed load acting perpendicular to the median surface of the plate; $\Delta = \frac{\partial^2}{\partial \mathrm{x}^2} + \frac{\partial^2}{\partial \mathrm{y}^2}$—Laplacian differential operator.

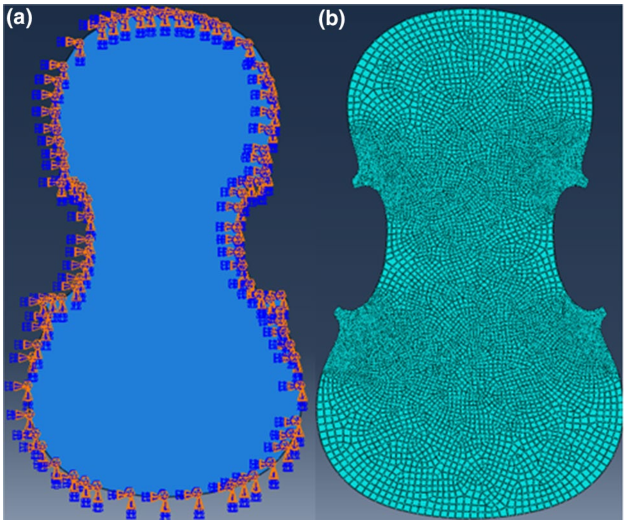


Fig. 4 Violin plate edge-constrained, in preprocessing step. **a** Boundary condition; **b** meshed structure

Table 1 Mechanical characteristics of wood as orthotropic material at 8–10% MC and 20–22 °C

Wood species	Density (kg/m^3)	Young’s moduli (MPa)			Shear moduli (MPa)				Poisson ratio				
		E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
S	420	14,128	8310	1441	5730	1975	1273	0.45	0.03	0.54	0.019	0.56	0.30
CM	712	11,700	6882	1194	1222	421	272	0.46	0.093	0.50	0.038	0.82	0.40
QM	740	9500	5588	969	1100	379	244	0.41	0.08	0.45	0.034	0.73	0.36
DUM	685	11,000	6471	1122	1200	414	267	0.44	0.09	0.48	0.036	0.78	0.38
NUM	605	9263	5449	945	1050	362	233	0.40	0.08	0.43	0.033	0.71	0.35

S spruce, *CM* curly maple with large wavy patterns, *QM* curly maple with small wavy patterns, *DUM* common maple with small and regular rings, *NUM* common maple with small and irregular annual rings

If $p(x, y, t) = 0$, Eq. (4) results in the free transverse vibration Eq. (5):

$$\frac{\partial^4 w(x,y,t)}{\partial x^4} + 2\frac{\partial^4 w(x,y,t)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y,t)}{\partial y^4} = -\rho \frac{h}{D}\frac{\partial^2 w(x,y,t)}{\partial t^2}, \tag{5}$$

To solve (4) the Fourier–Bernoulli method can be used, finding a solution in the form:

$$w(x, y, t) = w(x, y) \cdot w(t). \tag{6}$$

Using (6) in (5) results in (7):

$$\frac{D}{\rho h}\frac{1}{w(x,y)}\left[\frac{d^4 w(x,y)}{dx^4} + 2\frac{d^4 w(x,y)}{dx^2 dy^2} + \frac{d^4 w(x,y)}{dy^4}\right] = -\frac{1}{w(t)}\frac{d^2 w_t(t)}{dt^2} = \omega^2, \tag{7}$$

where ω is an arbitrary constant.

Equation (7) will result in Eq. (8):

$$\begin{cases} \frac{d^2 w_t(t)}{dt^2} + \omega^2 w_t(t) = 0 \\ \frac{d^4 w(x,y)}{dx^4} + 2\frac{d^4 w(x,y)}{dx^2 dy^2} + \frac{d^4 w(x,y)}{dy^4} = \omega^2 \frac{\rho h}{d} w(x,y) \end{cases}, \tag{8}$$

For the first Eq. (8) the solution is:

$$w_t(t) = A^{(t)} \cos(\omega t - \phi), \tag{9}$$

$A^{(t)}$ and ϕ are integration constants depending on boundary conditions. In this study, the clamped edges boundary condition was taken into account.

Patterns obtained with modal analysis are characterized by the orientation of nodal lines, and the presence of rings. The modal shapes obtained by FEA were compared to experimental ones. The vibrating surfaces of the plates determined experimentally were measured by transferring the nodal lines into the AutoCAD 2013 software, where the surfaces generated were expressed in mm^2 or in % of the total surface of the plate. The plates have no *f*-holes and are flat.

3 Results and discussions

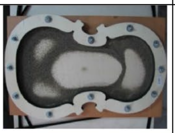
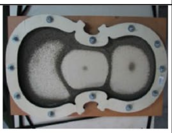
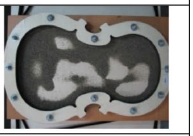
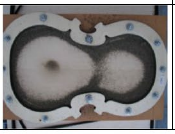
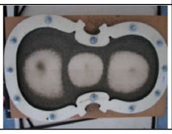
3.1 Experimental vibration mode patterns of five violin plates made of wood

In this chapter, the experimental vibration modes are presented. Experimental Chladni patterns of spruce plate (frequency range 110–2093 Hz) are very different from those of all other plates made of maple (frequency range 130.8 Hz and 2093 Hz). Table 2 shows the experimental vibration patterns for edge clamped plates and for five resonance frequencies. In the case of the spruce plate, for all frequencies, the nodal lines are parallel to the longitudinal axis of the plate. Most patterns show a symmetrical vibrating surface, with its large side parallel to the longitudinal axis of the plate, which is in fact oriented along the L anisotropic direction of wood. In comparison with spruce modal shapes, in the case of plates made of maple, the nodal lines of the vibrating surface are mostly oriented parallel to the width of the plate, corresponding to the R anisotropic direction of wood. The differences between dynamic responses of those wood species—spruce and maple are due to their different structures. Coming back to the experimental modes of vibration of plates illustrated in Table 2, the uniform grain structure of spruce wood is noted, which responds to a wide range of frequencies, where most of the nodal lines being formed parallel to the longitudinal axis of the plate.

Some asymmetrical patterns could be noticed in case of both low frequency (110 Hz) and high frequency (2093 Hz). The nodal lines for all plates made of maple and all frequencies are disposed mostly perpendicular to the longitudinal axis of the plate. Comparing the modal shapes of all tested plates made of maple, the most distinguished nodal lines for the first three frequencies are obtained in the case of plates made of curly maple (CM). For frequency of 130.8 Hz, the plate made of curly maple has a very asymmetric pattern. At 2093 Hz, this plate has great difficulty in vibrating, the vibrating surface. Wood behaviour in an acoustic field depends on the species, density, elastic properties, moisture content, chemical constituents of the cell wall, and the orientation of microfibrils in the cellular wall etc. (Bucur 2006b). A microscopic view of spruce and maple is given in Fig. 5. At the microscopic level, the medullary rays in spruce are rare, while in common maple the rays are abundant, and in curly maple, the rays are *very* abundant.

These results can be explained by the anatomical structure of the wood species of tested plates. Spruce has long tracheids of about 4 mm, and a well organised structure (Kollmann and Côté 1968). This anatomical structural organisation of the plate is reflected by symmetrical patterns, with the nodal lines well organised and parallel to the longitudinal axis of the plate, corresponding to the L symmetry axis of wood. By contrast, maple (*Acer* spp.) has short fibres ranging between 1 and 2 mm. For curly maple, the anatomical elements important in size are the medullary rays, oriented in the radial anisotropic direction of wood. When referred to the geometry of the plate, the rays are oriented along its width. This orientation of the medullary rays can explain the orientation of the nodal lines parallel to the width of the plate, which corresponds to the radial anisotropic direction of wood. In curly maple the rays are the dominant anatomical element when compared to maple of normal anatomical structure. In quilted curly maple, the plate's width is oriented along the T anisotropic direction.

Table 2 Experimental vibration patterns for five characteristic modal frequencies of edge pinned flat plates made of wood in the frequency range 110–2093 Hz

1	Spruce				
	110 Hz	588 Hz	784 Hz	1320 Hz	2093 Hz
					
2	Curly maple LR				
	261Hz	588 Hz	659 Hz	1320 Hz	1568 Hz
					
3	Curly maple LT				
	130 Hz	261 Hz	588 Hz	1320 Hz	2093Hz
					
4	Common maple regular annual rings				
	220 Hz	293 Hz	588 Hz	784 Hz	1320 Hz
					
5	Common maple, irregular annual rings				
	261Hz	329 Hz	588 Hz	784 Hz	1320 Hz
					

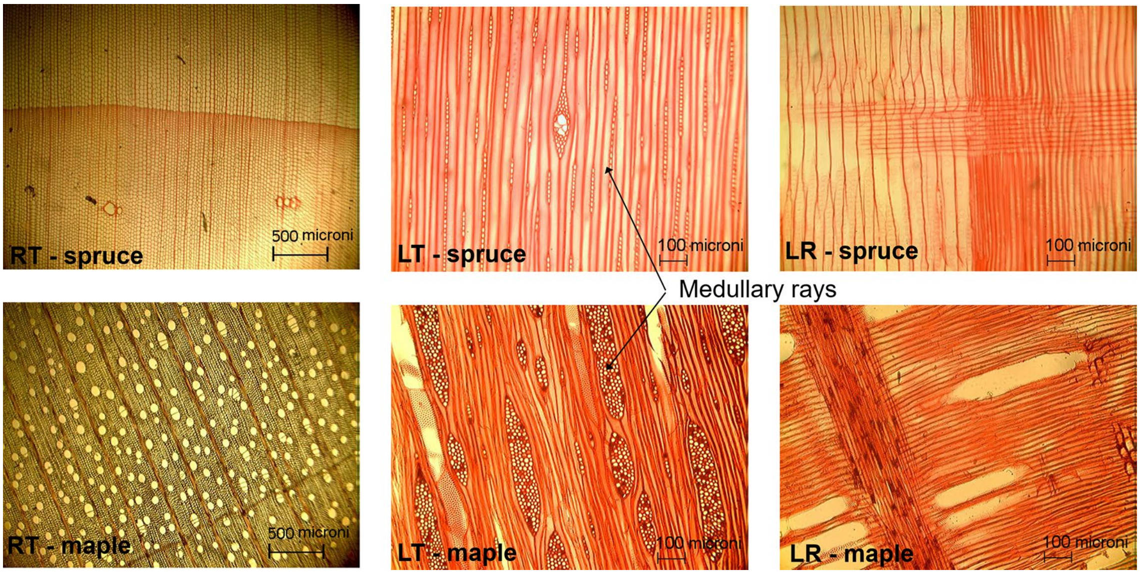


Fig. 5 Microscopic structure of spruce and maple of common structure (*RT* radial-tangential plane, *LT* longitudinal—tangential plane, *LR* longitudinal—radial plane)

This plate vibrates asymmetrically, and at higher frequency, the vibrating surface is very small.

This suggests that the alignment of medullary rays along the R direction is an argument in favour of the better resolution observed for the patterns of vibration modes on plates made of curly maple quarter sawn. On the other hand, at specific frequencies, correspondence can be noted between the wave length of vibration and the size of the anatomical elements, or groups of anatomical elements, which can favour the formation of patterns of better resolution.

3.2 Vibrating surface of plates

After OMA, the images with modal shapes for each frequency used in the experimental part were imported in AutoCad, where the contour of the nodal lines has been drawn and overlapped with the real patterns as can be seen in Fig. 6. Then, the surfaces delimited by the closed contours of the nodal lines were measured using the Area command. Thus, the values of the vibrating surfaces corresponding to the 36 frequencies to which each violin plate was subjected were extracted.

The effect of wood species on the vibration modes of the plates is studied with the following parameters:

- the effective vibrating surface (mm^2) of each plate calculated for each frequency; and total vibrating surface (mm^2) in the range of frequency 65–2637 Hz,
- the relative vibrating surface, which is the ratio of the vibrating surface to the total surface of the plate (%) in the range of frequency 65–2637 Hz;
- the vibrating surface (effective and relative) at maximum amplitude of vibration.

The vibrating area of the plates can be expressed by two parameters at each frequency, the effective vibrating area of plates expressed in mm^2 and the relative vibrating area expressed as % of the total surface of the plate. The total effective vibration areas for the totality of frequencies can also be calculated. A third parameter is the relative vibrating area (%) corresponding to the maximum vibration amplitude. Figure 7 shows the variation in effective vibrating area (mm^2) of plates versus each corresponding frequency, in the range 65–2637 Hz.

Total effective vibrating surfaces (mm^2) in the frequency range 65–2637 Hz for each plate and wood species are given in Fig. 8. The largest vibrating surfaces were recorded for curly maple plates, ranging between 80,665 and 84,295 mm^2 and the smallest surface was recorded for spruce plate, 53,093 mm^2. The effective surface of spruce plate is about 30% less than that of *Acer* spp. It can be seen that the plates made of maple (*Acer* spp.) have the capacity to amplify the vibrations of a top plate made of spruce. Referring to the parameter—total effective vibrating surfaces (mm^2)—the species can be classified as: curly maple small wavy pattern (QM) > curly maple large wavy pattern (CM) > maple common structure, annual rings small and irregular (NUM) > maple common structure, small annual rings and regular (DUM) > spruce (S). The spruce plate vibrating surface is the smallest.

Figure 9 shows the effect of frequency on relative vibrating surfaces, expressed in % from total surface of plate, in the frequency range 65–2637 Hz. Spruce has the smallest vibrating surface. For all species, several characteristic zones

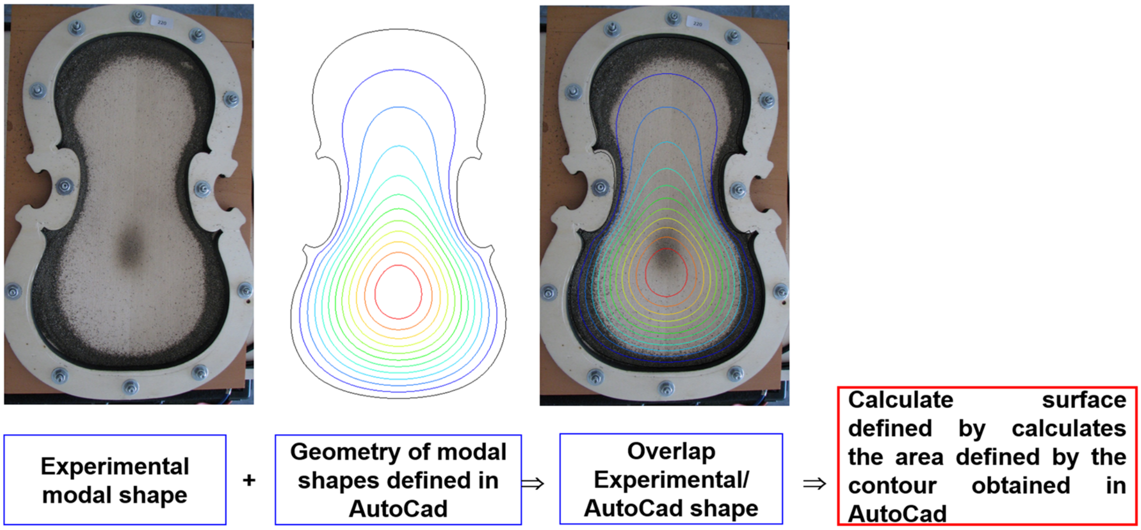
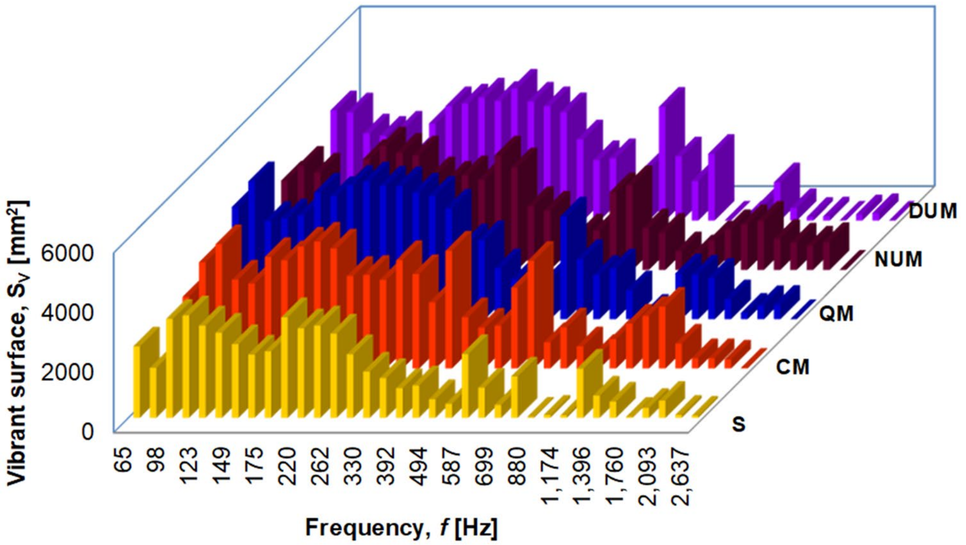


Fig. 6 Experimental image correlation with AutoCad tools

Fig. 7 Effect of frequency on effective vibrating surfaces (mm^2) of violin plates in the frequency range 65–2637 Hz



of frequency were observed: zone 1: 100–400 Hz, the vibrating surface is about 80%; zone 2: 400–800 Hz, the vibrating surface is between 40 and 70%; zone 3: 800–1200 Hz, the vibrating surface is very low, between 0 and 10%; zone 4: 1300–1700 Hz, the vibrating surface is about 20%; zone 5: 1800–2000 Hz, the vibrating surface is between 0 and 20%. A clear difference between spruce and curly maple can be seen at 600 Hz, the vibrating surface of spruce is 40% and that of curly maple is 68%. Equal vibrating surfaces for spruce and curly maple were obtained at 500 Hz, for 25% vibrating surface, at 1300 Hz for 30% vibrating surface and at 200 Hz for 3% vibrating surface.

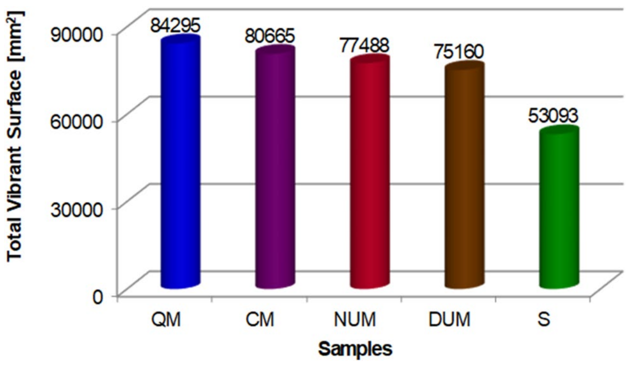
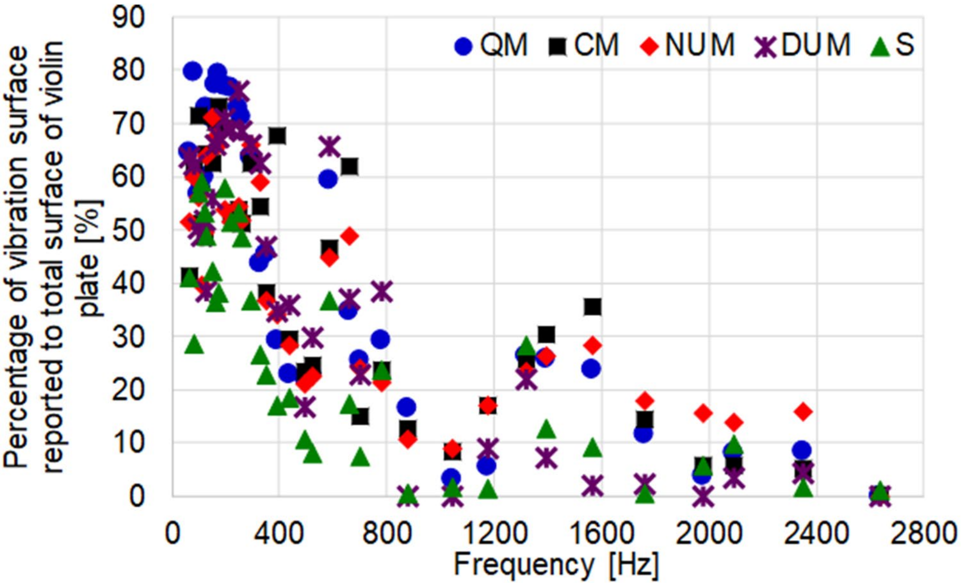


Fig. 8 Total vibration surface (mm^2) of plates by species in the frequency range 65 Hz and 2637 Hz

Fig. 9 Effect of frequency (Hz) on relative vibrating surfaces of plates (%)



3.3 Plate's forced vibration response to a specific frequency

Species and wood anisotropy have no effect on the vibration patterns for modes 1–6, just the magnitude of the vibrating surfaces differs from one sortiment to another as can be seen in Fig. 10. Similar modal shapes were recorded during OMA presented in Table 2.

The effect of wood species on the resonance modes of violin-shaped plates is summarised in Fig. 11. From this FEA simulation, it was deduced that each wood species has its own natural frequency. Modal frequency increases with increasing number of eigenmodes. The plate made of spruce has higher modal frequencies, while the maple plates have lower modal frequencies. Differences among plates made of

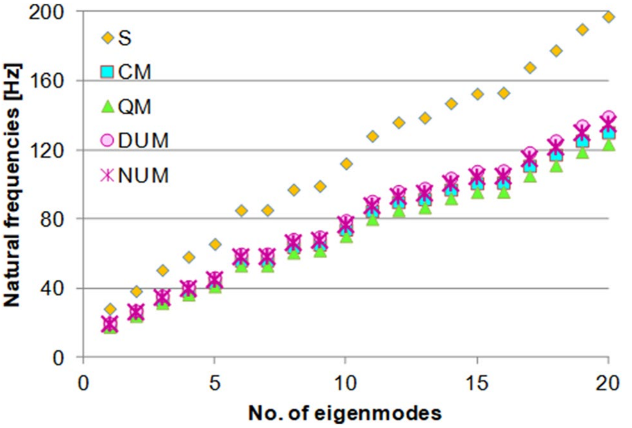
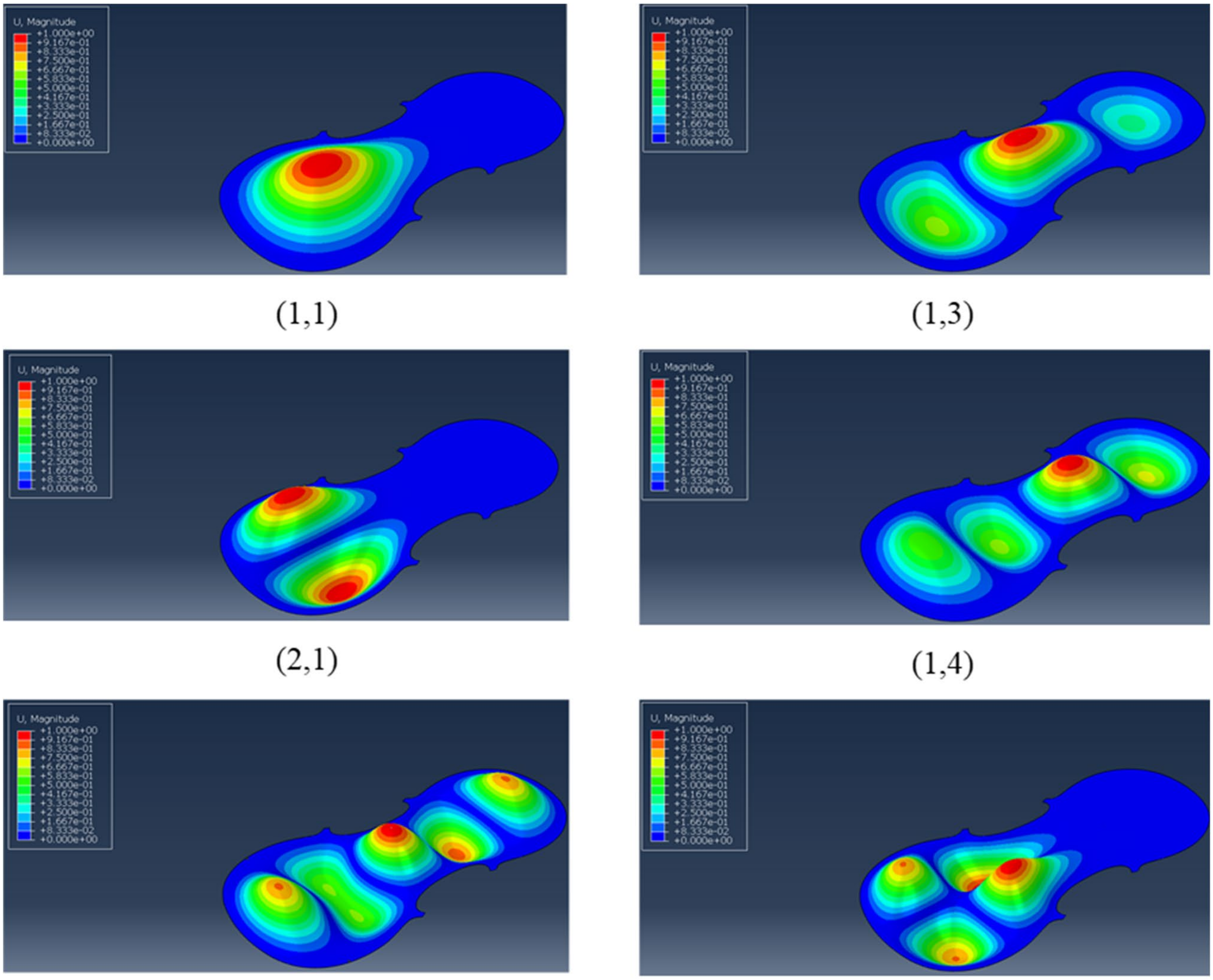


Fig. 11 Theoretical natural frequencies calculated for five plates made of wood versus the number of eigenmodes



(1,1) (1,3)

(2,1) (1,4)

(1,5) (2,2)

Fig. 10 Eigenmodes of violin plate

various maples are clearly visible for higher modes, above mode 10.

Simulation with FEA illustrates the vibration patterns of plates made of five wood species for the following specific frequencies: 196 Hz, 293.66 Hz, 440 Hz and 659.22 Hz corresponding to the fundamental frequencies of the tuning violin strings [sol (G), re (D), la (A), mi (E)] (Fig. 12). The vibration patterns of plates at their third harmonics: 588 Hz; 880 Hz, 1320 Hz and 1977 Hz are shown in Fig. 13. Qualitatively speaking, it can be noted that each plate made of a specified wood species has a characteristic pattern for a specific frequency and for all frequencies studied. The differences among patterns are more evident below frequencies of 500 Hz. Therefore, it can be concluded that the wood species have a characteristic effect on the vibration pattern of a violin plate.

3.4 Surfaces vibrating at maximum amplitude and the annual rings

3.4.1 Characteristics of annual rings

The characteristics of the annual rings of wood samples are shown in Table 3. Spruce (S) is characterized by very

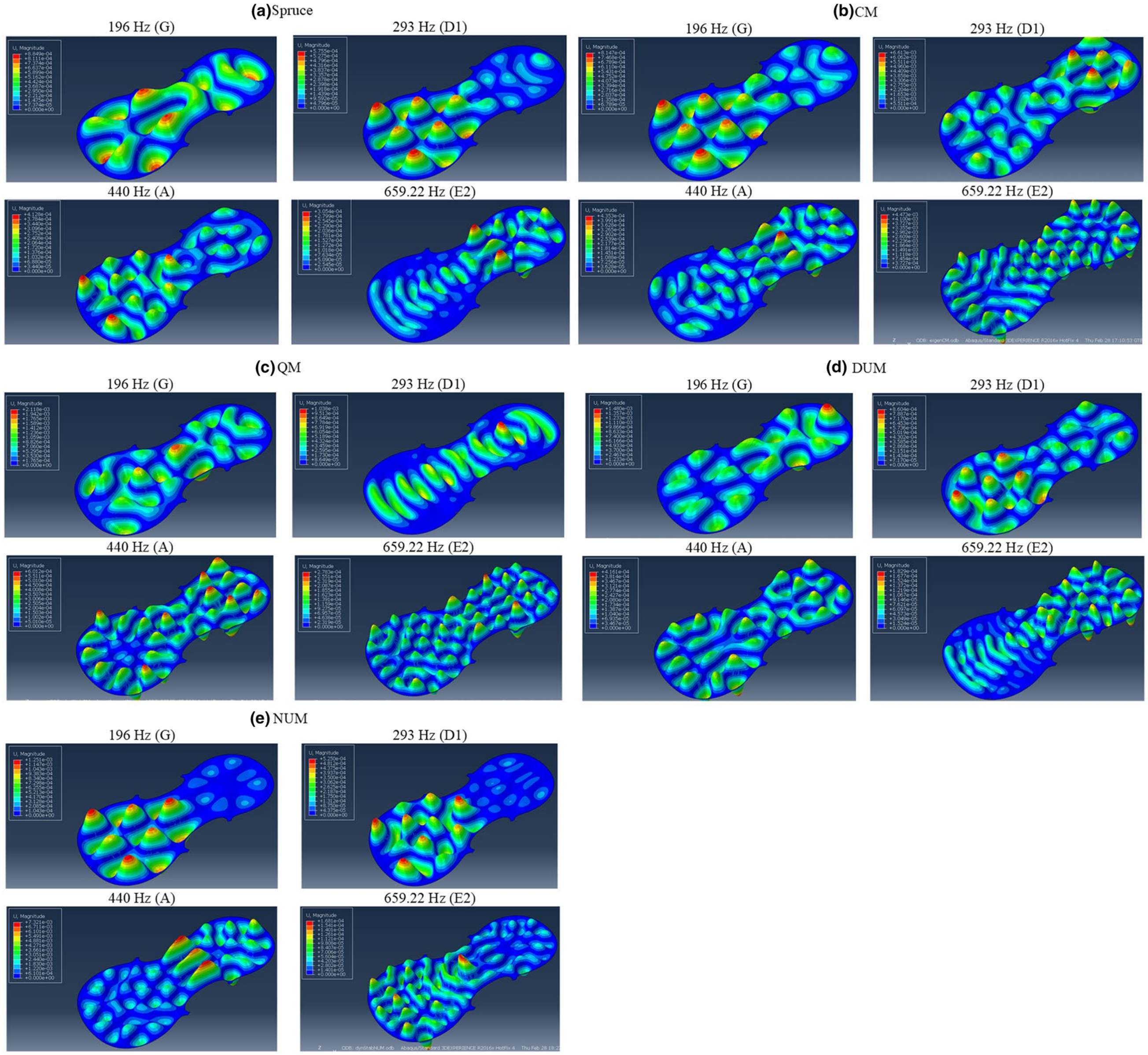


Fig. 12 Eigenmodes of violin plate made of five species, for the notes and the corresponding frequencies [G3 (196 Hz), D4 (293.7 Hz), A4 (440 Hz), E5 (659.3 Hz)]

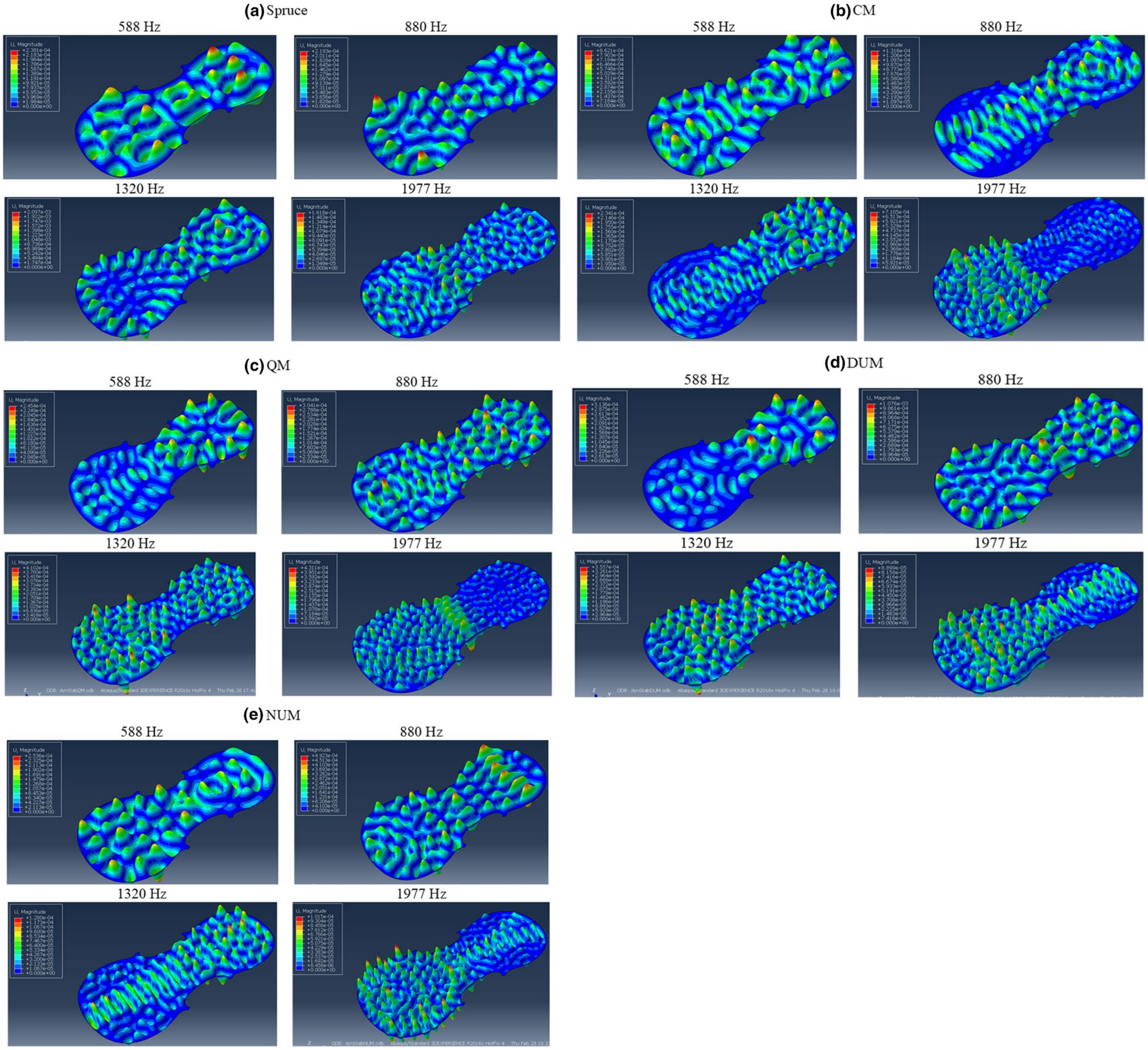


Fig. 13 Eigenmodes of violin plate made of five species for the third harmonics: 588 Hz, 880 Hz, 1320 Hz and 1977 Hz

fine annual rings. The mean width of the annual rings is 0.77 mm. The range of variation is between 0.1 and 2 mm. The most probable value of annual ring width is 1 mm; 30% of the rings have this width. The regularity of ring widths is very high at 91.6%. These characteristics of annual ring width are typical for spruce used for famous violins.

Curly maple of large wavy pattern (CM) has 1.57 mm mean width. The most probable width of the annual ring is 1.5 mm for 44% of rings analysed. The regularity of ring widths is also very high, 80%. Curly maple of small wavy pattern (QM) has the mean value of annual rings width of 1.59 mm, the most probable ring width is 2 mm and the regularity is 66.7%. Note the difference in regularity between the species traditionally used for violins, spruce and curly maple cut in the LR anisotropic plane (CM), and the curly maple cut in the LT plane (QM). As regards the common maple, the mean width of the annual ring is respectively 1.55 mm for the regular pattern and 1.67 mm for the irregular pattern.

Heterogeneity is lowest in value for spruce, 64.2%, which means that the spruce specimen has very regular annual rings. The highest value for curly maple specimen, denoted QM, is 238.98%. The heterogeneity of specimens of common maple is between 172.72 and 113.60%.

Pearson's asymmetry index shows large differences (60%) between maple of common structure of regular (+0.128) and

Table 3 Annual ring width parameters, measured on 30 rings

Annual ring parameters	Units	Wood species				
		S	CM	QM	DUM	NUM
Minimum width [W_{Min}]	mm	0.1	0.5	1.0	1.0	0.5
Maximum width [W_{Max}]	mm	1.2	2.5	3.0	2.5	3.0
Mean value [W_{Mean}]	mm	0.77	1.57	1.59	1.55	1.67
Standard deviation	mm	0259	0.504	0.448	0.299	0.570
Coefficient of variation	%	0.67	0.63	0.47	0.36	0.56
Most probable width	mm	1	1.5	2.0	1.5	1.5
	Proportion	36%	44%	30%	35%	27%
Pearson’s asymmetry Index [A]	–	− 0.32	− 0.112	− 0.870	+ 0.12	+ 0.319
Regularity [R]	%	91.6	80.0	66.7	75.0	83.3
Heterogeneity [HT]	%	64.2	86.9	238.9	172.72	113.60

irregular pattern (+ 0.319). In the case of spruce and curly maple specimens, this index has a negative value (− 0.320 for spruce and − 0.112 for curly maple CM). This tendency can be explained by the growth conditions of trees, causing very small annual rings in spruce and larger rings in curly maple. Data from Table 3 suggest that Pearson’s asymmetry index, calculated with three characteristics of annual ring—the mean, the most probable value and the coefficient of variation, is a valid parameter for the classification of wood species for musical instruments. Further research is needed

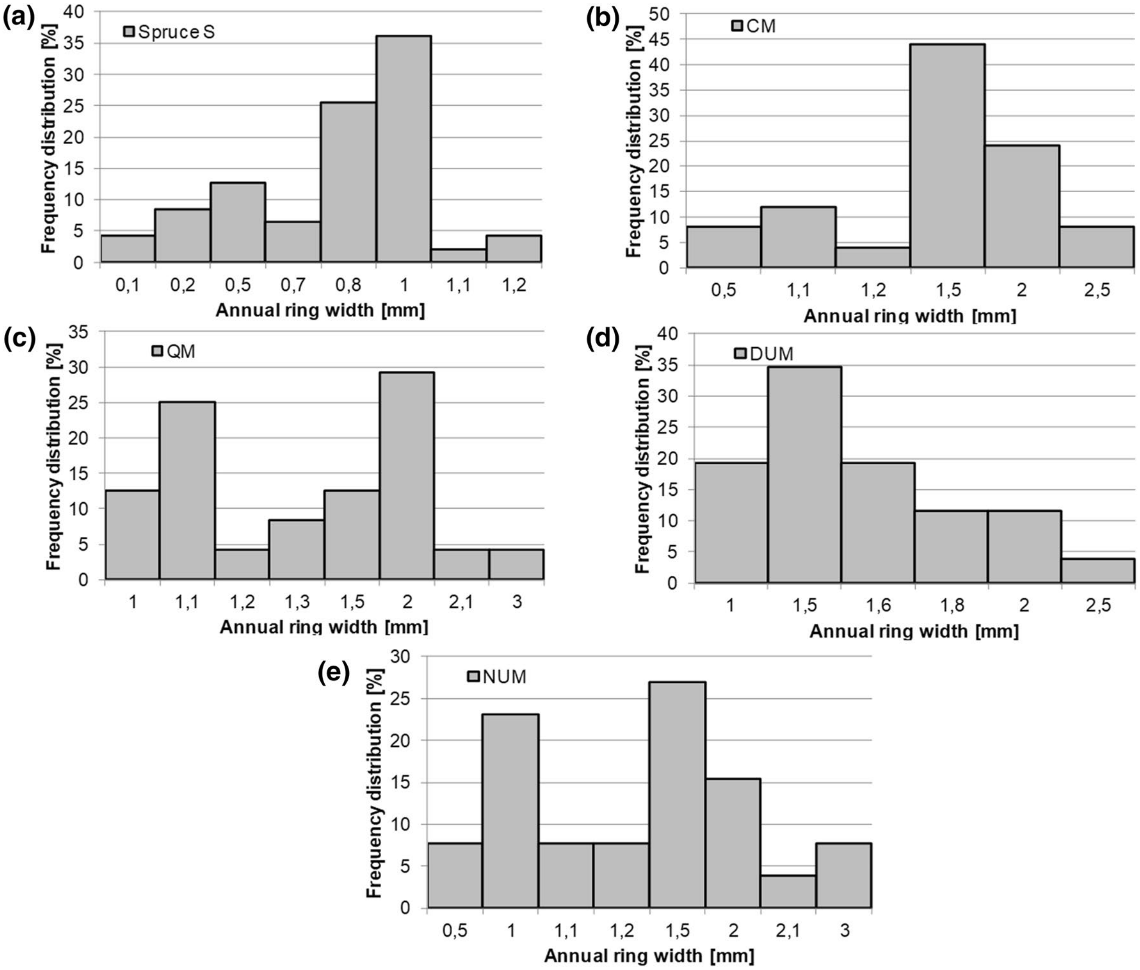


Fig. 14 Statistical frequency distribution of annual ring width

to identify other factors influencing this parameter, such as for example, additional classes for the frequency distribution, a larger variability of data, etc. Figure 14 shows the statistical distribution of annual ring width.

It can be noted that for spruce (*Picea abies L.*) plate, vibrating at a maximum amplitude of 110 Hz, the surface is 3418 mm^2, the relative vibrating surface is 62%, the annual ring mean is 0.77 mm; the regularity of annual rings is 91.6%, and the heterogeneity of annual ring width is 64.2%. For maple plates (*Acer* spp.), the maximum amplitude of vibration is between 148.8 and 246.9 Hz. CM and QM samples vibrate at the same maximum amplitude, 174.6 Hz, the size of vibrating surface being very close (4237 mm^2 for CM and 4602 mm^2 for QT). For CM plate, the annual ring mean is 1.57 mm; the regularity of annual rings 80%, and the heterogeneity of annual ring widths 86.9%. For the plate QM, the annual ring mean is 1.59 mm; the regularity of annual rings 66.7%, and the heterogeneity of annual ring width 238.9%. DUM plate vibrates at 246.9 Hz and the surface is 4408 mm^2 and the plate with irregular annual rings vibrates at 148 Hz; its surface is 4129 mm^2, the frequency at maximum amplitude is 246 Hz, the relative vibrating surface is 80%, the annual ring mean width 1.55 mm; the regularity of annual rings 75%, and the heterogeneity of annual ring width 172.7%. For the NUM plate, the relative vibrating surface is 75%, the frequency at maximum amplitude is 148 Hz; the annual ring mean width 1.67 mm; the regularity of annual rings 83.3%, and the heterogeneity of annual ring width 113.6%.

It can be concluded that at maximum amplitude of vibration, the plates made of curly maple (CM) and quilted maple (QM) have different behaviour compared to other specimens tested. At maximum amplitude, the behaviour of the plate made of spruce is very different, due to anatomical structural particularities. The heterogeneity of annual rings is 64% for the plate made of spruce. This specimen is of exceptional quality as resonance wood. The heterogeneity of annual rings of curly maple (CM) with dense figures is 86.9%.

In the case of plates made of curly maple, at the same frequency 174.6 Hz, the relative vibrating surface is greater for the plate of curly maple (QM) with dense figures than for the plate of curly maple (CM) with less dense figures. Therefore, it can be noted that curly maple has two roles in violin manufacturing: an aesthetic role but also an acoustical role.

4 Conclusion

The effect of wood anisotropy on the vibration modes of flat violin plates made of spruce and maple was demonstrated both experimentally and with FEA using the hypothesis of orthotropic materials. The experimental vibrating surfaces of the tested plates were measured by transferring the nodal lines into the AutoCAD 2013 software, where the surfaces were computed and expressed in mm^2 or in % of the total surface of plate. The effect of wood species on the vibration modes of five violin plates having a large variety of wood anatomic structure was studied based on the vibrating surface of the plate and of the characteristics of the wood's annual rings. Analysing the characteristics of the width of the annual rings of wood for the plates and the total of vibrating surface at maximum amplitude, it was shown that the plates made of curly maple (denoted QM and CM) have bigger vibrating surfaces than the plates made of spruce. Consequently, the plates made of curly maple can amplify the vibrations of plates made of spruce. The behaviour of plates made of curly maple is different from that of plates made of maple of common structure. Evidently, the curly pattern has an important role in the mode of vibration of plates, and not only in the aesthetics of the violin. The traditional combination of species for violin making—spruce for the top and curly maple for the back is effective when referring to the vibrating surface of plates.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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