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Influence of orthotropic properties on vibration of violin top plates

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ABSTRACT

In this paper the mode vibrations of violin plates are investigated by numerical simulations. The plate geometry is scanned by means of a 3D laser scanner. Numerical simulations are performed using Finite Element Methods, in order to retrieve eigenmodes and mode shapes. The orthotropic properties of wood such as maple and spruce are introduced in the numerical simulation. We show that the shapes of the main modes calculated by numerical simulations are in good agreement with those of a real violin. We discuss how material properties influence the eigenmode frequencies and shapes.

Keywords: Violin, Mode shape, Orthotropic material, Numerical Simulation

1. INTRODUCTION

Many studies about mode vibration of violin and sound radiation have been proposed during the years, see for example [1-3], but it is very difficult to obtain results with a neat interpretation from a quantitative and even qualitative standpoint. The shape and the dimension of current violin were settled by A. Stradivari (1644-1737) et al. before about 300 years ago. The mechanical properties of these instruments cannot be studied in detail, due to the requirement of performing completely noninvasive analyses. It is therefore impossible to infer the mechanical properties of the wood of the historical instruments and therefore, even if the same geometry of the reference instrument is used, there is no way of obtaining a perfect acoustic copy.

As a consequence, numerical simulations based on Finite Element Method (FEM) and Boundary Element Method (BEM) have gained importance in the last few years for the analysis of the vibration of violin plates [4,5]. In this paper we focus on the problem of assessing how the Young's modulus and density of the material impact on the eigenfrequency of the mode 5 (also known as "ring mode"), which is deemed as important to determine the resonances of the violin body. At knowledge of the authors, this study has not been conducted in the literature, yet. Moreover, in this paper we conceive the numerical analysis as a coupled problem between mechanical vibration and the sound field produced by the vibration. Also, the coupling has received minor attention in the literature.

More specifically, in our study we conduct a numerical simulation (through FEM and BEM) of vibrational modes of the back plate of a violin whose geometry has been obtained by a precise 3D laser scanner, and we investigate the influence of the mechanical properties of the wood (maple in the case of back plates of the violin) on mode vibration for a range of possible values.

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2. Method

2.1 Scanning violin surface and generating mesh for mechanical simulation

In this section we shortly describe the measurement of the 3D geometry of the plate from laser scanning. We used a plate with a finished outline, arch and thicknesses. The body length is 352 mm and the weight is 123 g. The mean density estimated from the volume and weight is 0.637 g/cm^3. A single violin has been used for this study.

Figure 1 shows the snapshots of scanning the surface of violin, revising the geometry and importing the mesh used for numerical simulation. The resolution of laser scanner, Romer ABSOLUTE ARM, is 0.01mm at the minimum. We took both the external surface and internal surface of back plate of violin and combined them using the Polyworks™ software by InnovMetric. A stage aimed at removing all the small holes and unavoidable imperfections generated during the scanning has been accomplished before the creation of polygon data in the STL file. The polygon data was imported in the COMSOL Multiphysics™ software, and the three-dimensional geometry by tetrahedron mesh was generated by the automatic mesh function offered by COMSOL Multiphysics. The number of vertices used is approximately 234k, and the eigenfrequency and mode shapes were calculated by the finite element method.

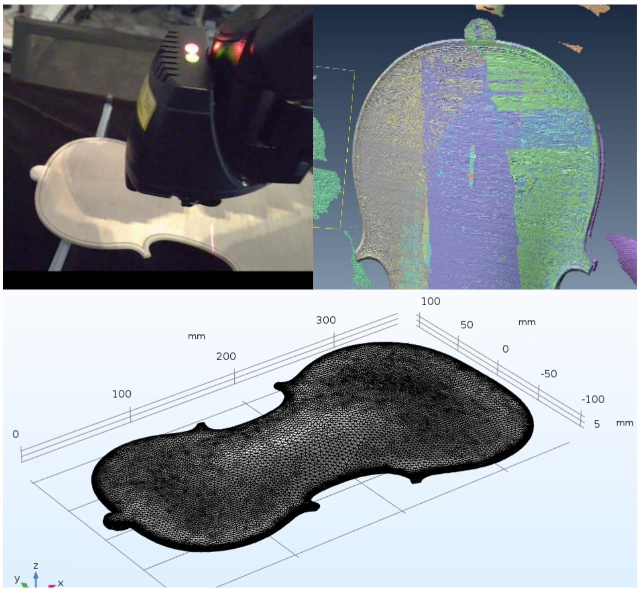


Fig.1 Snapshots scanning the surface of violin back plate (upper row, left), revising the geometry (upper row, right) and importing the mesh data to COMSOL Multiphysics (lower row).

2.2 Setting of orthotropic property of wood

In order to setup accurate simulations, it is of utmost importance to set the mechanical properties of the material, which in this case is wood. Wood is an orthotropic material [6, Chap. 1], as it exhibits different mechanical properties along three main axes, which are determined by the grain, radial and tangential directions. Spruce and maple blocks for violinmaking are usually cut as shown in Fig.2.

The nominal mechanical properties of the material that are used in the simulations are shown in Table 1 [7]. Here, the values of E_T and E_R are expressed in terms of the ratio with the Young's modulus along the longitudinal direction, E_L. It is important to notice that different samples of maple exhibit values of E_L that can greatly differ from the nominal value reported in Table 1. Moreover, it is difficult to measure the accurate Young's modulus of a plate when its arch has been already sketched.

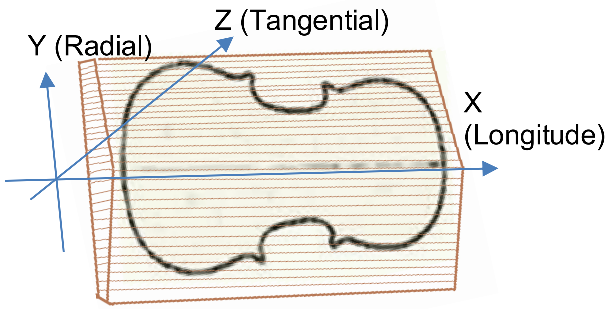


Fig.2 Orthotropic property of violin plate. Because wood is orthotropic material, we set the typical (or real) value of orthotropic properties of the wood to the parameters of COMSOL Multiphysics.

Table 1 Values for Orthotropic properties for setting in numerical simulation

Property	Value
Young's module E_L	12.6(GPa)
E_R / E_L	0.132
E_T / E_L	0.065
Rigidity modulus G_{LR} / E_L	0.111
G_{RT} / E_L	0.021 *
G_{LT} / E_L	0.063
Poisson's ratio μ_{LR}	0.424
μ_{RT}	0.774
μ_{LT}	0.476

* G_{RT} is assumed by the average of other hard woods because the value is not showed in the article[7].

3. Simulation Result

3.1 Comparison of mode shape between virtual thickness and real thickness

The thickness of plate of violin is not uniform along its extension. In particular, the central part of the plate is the thickest and the thickness gradually become thinner toward the peripheral part. More specifically, the thickness at the edge is in the range 4.2 - 4.5 mm, whereas 3 cm inside from the edge of lower bouts and upper bouts it is in the range 2.0 - 2.5 mm. The exact values of the thickness depend, of course, on the choices of the violin maker.

Thus, the thickness has a very relevant impact on the vibrational behavior of the plate. As a first study, we compared eigenfrequencies and modal shapes obtained from the actual 3D geometry, with those of a plate with a uniform thickness. We analyzed three modes, which are deemed as important by violinmakers, which are namely mode 1, mode 2 (also known as "cross-mode") and mode 5.

The eigenfrequencies were different for all the modes under analysis. Moreover, the nodal lines (i.e. the regions of the modal shapes with zero displacement) of mode 1 and mode 2 are similar, whereas the nodal lines of mode 5 are different, as the nodal line exhibits a rounder pattern when the real thickness is used. This rounded contour matches with the experimental results obtained with the Chladni analysis on the same back plate (Fig. 4).

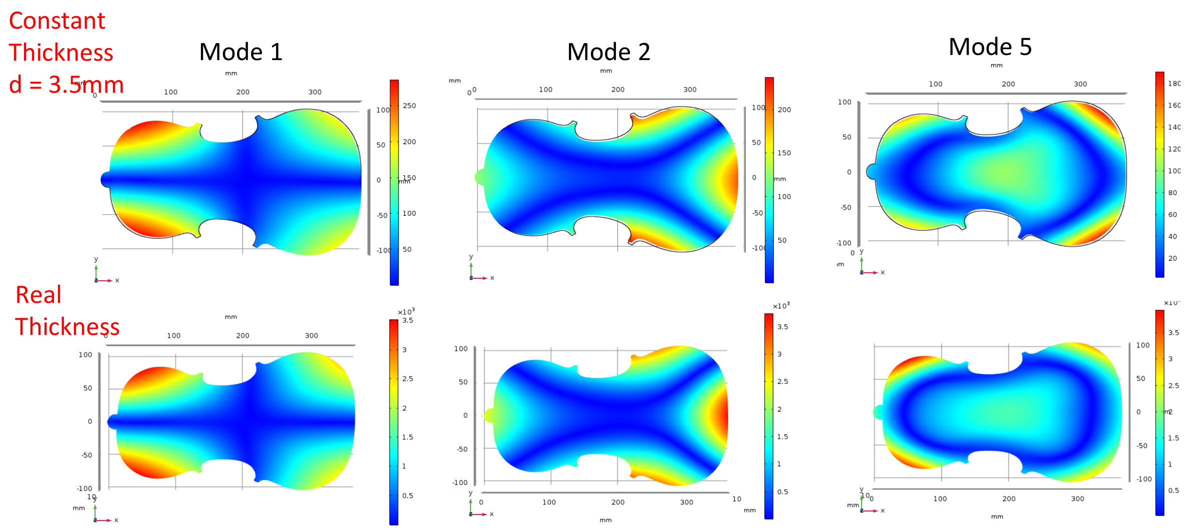


Fig.3 Mode shapes of back-plate of violin, (a) mode 2 (x-mode), (b) mode 5 (ring mode).

Fig.4 Mode shapes (mode 2, 171 Hz, and mode 5, 352 Hz) of back-plate of violin by Chladni Method.

This experimental validation proves the importance of using the real thickness in modeling the vibrational behavior of the plates, and it is easy to guess how it is important also for the violin body with assembled plates. It is important to notice that the measurement of the thickness is not always possible for historical instruments.

In the process of violin making, violin makers adjust and finish the thickness and arch of violin plate so that the eigenfrequencies match target ranges. In particular, the eigenfrequency of mode 5 is known as “tap tone” which many violin makers hear from old days. It is generally adjusted to 340 - 350Hz in a back plate.

When the nominal value E_L = 12.6 GPa of the Young’s modulus is used, the eigenfrequency of mode 2 was 150 Hz, that of mode 5 was 340Hz. On the other hand, by the Chladni method, the eigenfrequency of mode 2 was 171 Hz and that of mode 5 was 352 Hz. We interpreted this difference as a consequence of the deviation of the mechanical properties of the wood under analysis from the nominal ones. If we ascribe the different behavior to the Young’s modulus only and we keep the remaining parameters to the nominal values, we need to increase E_L to 13.5 GPa, approximately 7.2% upper than the representative value, in order to obtain the same eigenfrequencies of the sample violin.

3.2 Impact of the properties of wood on the eigenfrequency

Figure 5 plots the eigenfrequency of the modes as a function of the thickness of the central part of the plate, expressed in millimeters. The thickness of the rest of the plate was scaled proportionally. The actual thickness of the central part of the plate under analysis was 4.0 mm. The range of thicknesses in our numerical simulation was set from 3.5 mm to 4.2 mm, here the range is general thickness when violin makers make a violin.

In order to modify the thickness of the plate, we developed an ad-hoc algorithm that modifies the z-coordinate of the outer mesh (the mesh of inside arch is fixed), once the representative value of the thickness at the center of the plate is given. It is possible to notice from Fig. 5 that for both modes 2 and 5, in the considered range there is a linear relationship between eigenfrequency and thickness.

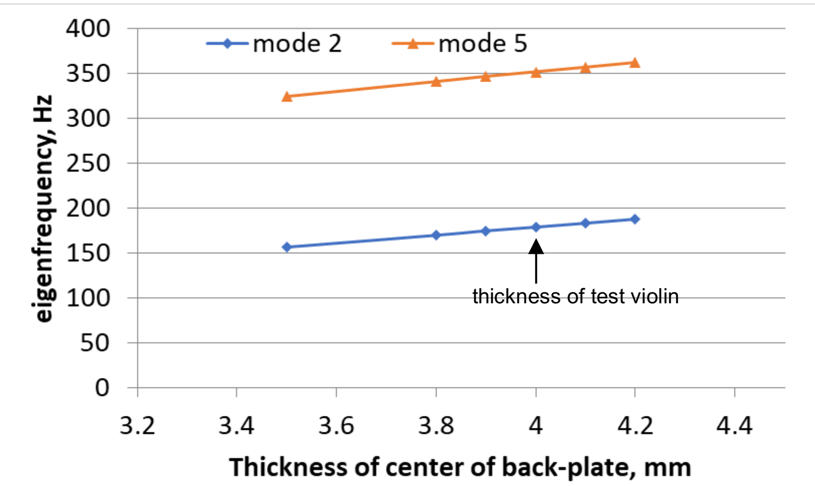


Fig.5 Change of eigenfrequency by the change in thickness of back plate. The thickness in horizontal axis is the thickest point in the center of back plate. 4.0 mm is the thickness of test violin used in this study.

On the other hand, we could be interested in assessing the impact of a modification of the Young's modulus on the eigenfrequency. Figure 6 and Figure 7 show the variation of the eigenfrequency when the Young's modulus and the density span in the range from -20% to +20% of the nominal value. This range has been suggested by violinmakers. We notice that if the elasticity in the grain direction, E_L, increases, the eigenfrequencies of mode 2 and mode 5 become higher. Conversely, if the density increases the eigenfrequencies decrease.

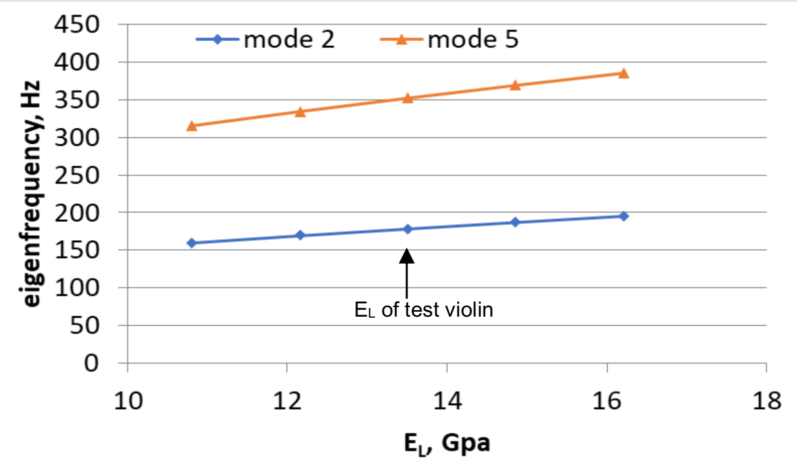


Fig.6 Change of eigenfrequencies by the difference in E_L of back-plate.

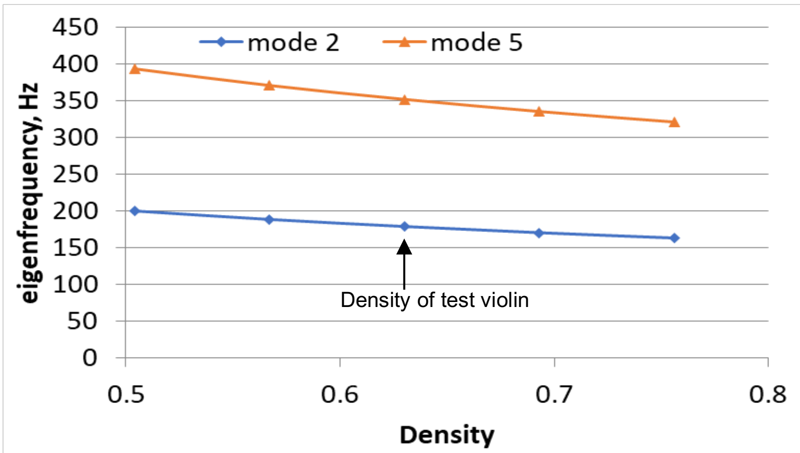
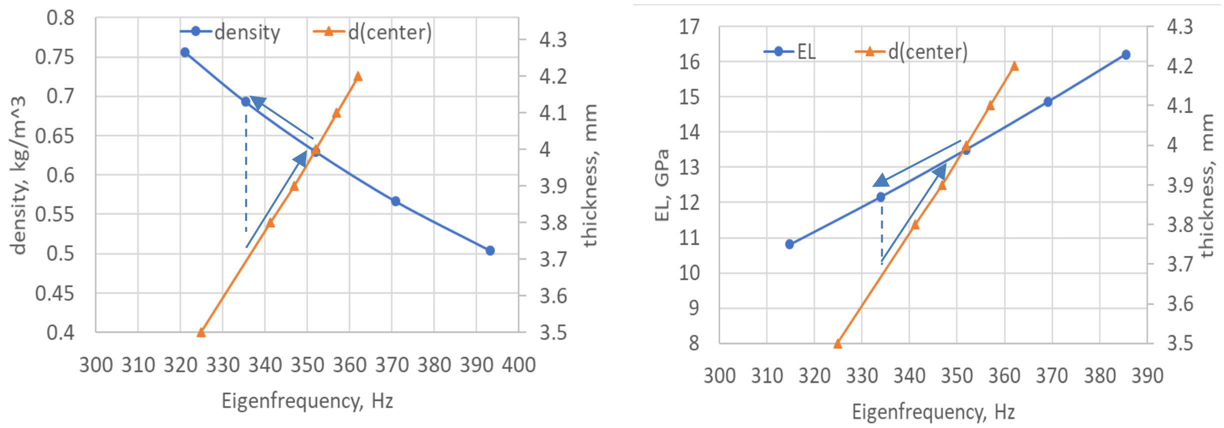


Fig.7 Change of eigenfrequencies by the difference in density of back-plate.

In practical situations, one could be interested in determining the thickness of a plate when the Young's modulus differs from the nominal value so that the eigenfrequencies match with the target values. For this purpose, Figure 8 shows the relation between the density, the Young's modulus, the thickness at the center of the plate and the eigenfrequency, under the assumption that the three variables are independent each other. As mentioned above, violin makers check the eigenfrequency of the mode 5 listening to the tap tone and, based on this, trim the arch and the thickness of the plate so that the mode frequency falls in the range from 340 to 350Hz. Figure 8 quantifies the modification of the thickness of the plate so that the eigenfrequency increases or decreases when the elasticity and density of wood change.

As an example, it is possible to notice from Fig. 8(a) that when the density increases by 10%, the frequency decreases approximately by 16Hz. To restore the frequency of 352Hz of the mode 5, the thickness must be increased by approximately 0.3 mm. Moreover, from the inspection of Fig. 8(b), we can notice that when E_L decreases by 10%, the frequency decreases approximately by 18Hz. To keep the eigenfrequency of 352Hz, a violin maker should increase the thickness of the plate approximately 0.3 mm.

However, it is important to stress that the Young's modulus and the density are not independent variables, and therefore we cannot directly apply the rule of thumb proposed above simply. Nonetheless, this analysis gives us some ideas, at least qualitative, of the trend.



(a) density v.s. thickness (b) E_L v.s. thickness

Fig.8 Change of mode 5 eigenfrequency and relation between thickness $d_{(center)}$, density and elasticity.

4. CONCLUSIONS

In this study we performed a numerical simulation of the vibration of back plate of violin by the finite element method using COMSOL Multiphysics and analyzed the tendency of the change of the vibration mode by the change of the physical characteristics of maple. The analysis of these relationships by the change of physical characteristics helps violin production, and it is thought that these analyses contribute the analysis of the sound of historical Italian violin in future. Focusing on the acoustic radiation from a violin body, now we are preparing the geometry of not only back plate of a violin but also whole body and parts, and we will simulate numerically the coupled problem of structure and acoustic in near future.

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