The Acoustics of Traditional Italian Mandolins and Their Relation with Soundboard Wood Properties

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Abstract

Stringed musical instruments, which have a long and rich worldwide cultural history, have slowly evolved from ancient lutes to contemporary instruments such as the Italian mandolin. The mandolin has been an iconic element of Italian musical tradition and culture for more than 400 years. In this study, we report on the acoustic characterization of modern Italian mandolins in terms of bridge admittance, sound radiation, and modal shape measurements. The vibrational behavior of the soundboard was studied by means of finite element analysis (FEA) to establish a link between the mechanical and physical properties of wood and the acoustic response of the instrument. This study presents some important features of the acoustic behavior of mandolins and sheds some light on the influence of wood properties on the instrument’s timbre and its variability.

Keywords

musical instruments – mandolin – acoustics – vibration – wood mechanical properties
Introduction

A Brief History of the Mandolin

Stringed musical instruments have been part of worldwide culture since ancient times with traces of lutes dating back to 3000 BC. Historical research reveals that these instruments have spread all over the world because of wars, emigration, and cultural influence and slowly evolved while geographically spreading. Notably, the ancient lute eventually transformed into the Islamic oud, which was then brought to Spain during the conquest of the Moors and later to Sicily. In the past few centuries, it continued evolving as different bowlback instruments — among which was the actual mandolin (Sparks 1989; Sadie & Tyrrel 2001). In particular, an example of a contemporary mandolin is shown in Fig. 1. One of the most significant and successful developments of this family of instruments was related to the Neapolitan mandolin in the first half of the eighteenth century. This instrument initially featured gut strings and a flat soundboard but continued to evolve until the beginning of the nineteenth century, when the sound requirements of musicians and composers brought about the use of metal strings. A larger string tension leads to important modifications such as the use of a third reinforcing brace and the introduction of a bent soundboard (Woll 2021). This renewed model was established as a modern mandolin and remained almost unchanged until today. From a musical point of view, several well-known musicians and composers — including Antonio Vivaldi — considered the mandolin as worthy as the violin, and several of his compositions feature

![Figure 1](https://example.com/image1.png)

**Figure 1** A contemporary classical Italian bowlback mandolin built during this study. Front, side and back views are shown from left to right.
mandolin solos and mandolin orchestras (Bone 1914). During the last two centuries, the mandolin has been widely developed and dispersed all over the world. Accordingly, the Italian mandolin tradition continues and, presently, thousands of people play this instrument and its descendants both for classical and for more modern repertoires such as bluegrass or folk (Tyler & Sparks 1996; Mc Donald 2016).

1.2 Mandolin Materials and Acoustics
Since the late Renaissance period, the habit of stringed musical instrument makers was to use European spruce (or Norway spruce (Picea abies)) for the realization of soundboards. In fact, this wood has excellent acoustical properties due to a peculiar combination of mechanical properties and low density (Bucur 2016); moreover, its use has become an integral part of a luthier's standard practice. Italian mandolins also follow this tradition, and their soundboards are typically made of European spruce. As for the other parts, mandolins show a wide variety of wood species (e.g., maple (Acer spp.), rosewood (Dalbergia spp.), cherry (Prunus spp.) and walnut (Juglans spp.)), in contrast with the violin-making tradition where maple is the primary material of choice. From a scientific point of view, it is interesting to measure the acoustic properties of stringed instruments and relate them to the wood properties or to the instrument design. In this regard, numerous publications can be found on the acoustic characterization of the most common bowed and plucked musical instruments, such as violins or guitars (Fletcher & Rossing 1998; Woodhouse 2021). Conversely, not much can be found regarding mandolins and, in particular, bowlback mandolins. In a pioneering study, Cohen and Rossing (Cohen & Rossing 2003) measured the sound spectra and vibration modes of bluegrass American mandolins, while another study only studied the chemical composition of varnishes and decorations of some historic Italian mandolins (Rovetta et al. 2014).

1.3 Aim and Outline of this Study
In this study, we aim to analyze the acoustics and vibrational behavior of modern mandolins to understand their working principles and establish a link between wood properties and sound. In the second section the materials and methods are described and a brief introduction is given about the research project that financed this work. Then, in the third section, we report the measurements of the acoustic and vibrational properties of some modern mandolins in terms of bridge admittance, sound pressure level, and modal shapes, as well as finite element analysis (FEA) simulations that aim to establish a link between the wood properties and soundboard behavior.
2 Materials and Methods

2.1 World Wood Day Foundation Research Project Background
This study was carried out during the research project, Choice of Wood in Musical Instruments: Italian Red Spruce and Traditional Mandolins, a study funded by a World Wood Day Foundation research grant in 2019. This project had three main tasks: (1) to measure and understand the acoustic behavior of classical Italian mandolins; (2) to establish a link between the properties of wood used for the soundboards and the acoustic response of the instruments; and (3) to build a mandolin using the knowledge gathered during the research. In this article, we focus on the first two topics, while the third topic will be discussed in future pieces. Another part of this research concerns the grading of wood for musical instrument making and was published separately (Quintavalla et al. 2022).

2.2 Experimental Setup
2.2.1 Acoustic and Accelerometer Measurements
Acoustic measurements were performed by exciting the soundboard with an impact hammer (Dytran 5800SL) and measuring the soundboard acceleration using an accelerometer (Dytran 3225F), as well as the sound pressure level with an internal and external microphone. The sound radiation inside the mandolin body was measured with an omnidirectional electret capsule (Panasonic WP61) held against the back with a small magnet. The sound radiation outside the mandolin body was measured with a calibrated microphone (Beyerdynamic MM1) placed 60 cm from the soundboard. The procedure is similar to that developed for violins (Curtin 2009). The accelerometer was installed on the soundboard with wax, close to the position of the G string (bass side); so, the soundboard was excited by hitting the bridge bone with the impact hammer very close to the accelerometer to measure the driving point admittance \( Y \). This measurement is representative of the response of the entire soundboard of mandolins (Taguti & Yamanaka 2006). Specifically, the setup is shown in Fig. 2.

2.2.2 Measurement of Eigenmode Shapes
Modal shapes were determined using the Chladni pattern technique. The soundboard was excited with a loudspeaker, using a sinusoidal signal with a frequency corresponding to that of the mode, as observed from the spectrum peaks. Furthermore, some wood powder was spread all over the soundboard so that once the soundboard vibrated, the powder was displaced from the antinodes (where the soundboard movement was maximum) and collected at nodal lines (where there was no movement). Although Chladni patterns highlight...
operational deflection shapes rather than eigenmodes, at low frequencies where modes are well separated, their shapes correspond quite accurately (Richardson 1997); hence, they can be considered as a correct representation of nodal lines.

2.3 \textit{Finite Element Analysis (FEA)}

FEA simulations were run using COMSOL Multiphysics software. To perform the simulations, we used the same material properties as of the wood used for the instrument named WWDF-1. These properties were determined from wood blanks before building the instrument, using nondestructive techniques based on the measurement of the vibration frequencies of the panels (Caldersmith & Freeman 1990; Quintavalla \textit{et al.} 2022) and are reported in Table 1.
2.3.1 Relation between Density and Mechanical Properties

Because the elastic properties are related to the wood density, we included this relation in the FEA. In particular, we referred to the data acquired during our previous wood characterization campaign (Quintavalla et al. 2022). The trends of the elastic moduli as a function of wood density are shown in Fig. 3. Despite the fact that the data are quite scattered — especially $E_R$ and $G_{LR}$ — there is a clear trend, especially for the longitudinal elastic modulus, which is the most important parameter in determining the eigenmode frequencies (see Section 3.2.2). Based on this consideration, we included the linear dependencies shown in the equations of Fig. 3 in the FEA by assigning to the moduli a parametric expression (function of density) and then by performing a parametric sweep on density.

2.4 Mandolin Construction

During the project, the authors built three experimental mandolins. These mandolins share the same visual aspect and the same material and geometry for each component, except for the soundboards that differ in thickness, geometry, and bracing. A picture of these mandolins is shown in Fig. 4. In this study, only one of the mandolins, named WWDF-1, was analyzed. A comparison of the three mandolins will be conducted in future studies.

### Table 1

| Density (kg/m\(^3\)) | $E_L$ (GPa) | $E_R$ (GPa) | $G_{LR}$ (GPa) |
|-----------------------|------------|-------------|----------------|
| 316.2                 | 9.36       | 0.53        | 0.70           |

Notably, $E$ and $G$ are the elastic modulus (Young modulus) and shear modulus, respectively. Subscripts L, R, and LR indicate longitudinal, radial, and torsional directions, respectively.

**Figure 3** Mechanical properties (elastic moduli) of Norway spruce expressed as a function of density for some of the wood samples characterized in (Quintavalla et al. 2022). The results for $E_L$ (blue) and $E_R$ (red) and $G_{LR}$ (yellow) are shown in two different plots for clarity.
3 Results and Discussion

3.1 Acoustic Properties of Classical Italian Mandolins

3.1.1 Soundboard Admittance and Acoustic Radiation
To study the acoustics of mandolins, we measured the bridge admittance and acoustic radiation from the soundboard. These measurements quantify how the soundboard is capable of radiating sound waves in air once it is forced to move by the vibrating string forces acting on the bridge. From the signals collected, we measured the bridge admittance $Y$ and sound pressure level (SPL), as shown in Fig. 5, for four different mandolins. The mandolins analyzed in this work are three historical mandolins that are representative examples of the modern mandolin and its variations across Italy: an E. De Cristofaro mandolin of 1906 (Naples); an A. Monzino mandolin of 1908 (Milan); and an anonymous mandolin at the beginning of the twentieth century, realized according to the Roman style. The fourth mandolin was built by the authors during the World Wood Day Foundation project and is a contemporary interpretation of the modern mandolin type. Similar to other instruments such as violins and guitars, it is possible to distinguish a low-frequency response (up to approximately 2 kHz), where peaks corresponding to eigenmodes are well separated. This range corresponds to the signature mode of the mandolin. An example of the signature modes of the mandolin named WWDF-1 realized during the research project (see Figs 1 and 2) is shown in Fig. 6.
Figure 5 Example of bridge admittance $Y$ (above) and sound radiation (below) spectra of some historical and contemporary mandolins. Spectra are spaced apart by 30 dB from top spectrum for clarity. The mandolins are three examples of modern mandolin by the different schools of Naples (De Cristofaro, 1906), Milan (Monzino, 1908) and Rome (Anonymous, beginning of the 20th century). Mandolin WWDF-1 was built by the authors during the World Wood Day Foundation project in 2019 and is a contemporary interpretation of the modern mandolin type.

3.1.2 Signature Modes Assignment by Modal Shapes Measurement

Sound radiation is affected not only by frequency response curves, but also by eigenmode shapes. To be consistent throughout the article, we adopted the same nomenclature as Gore and Gilet (Gore & Gilet 2011), where a letter — in this case, $T$, indicating the top or soundboard — is followed by two numbers between the parentheses which indicate the number of antinodes along the transversal and longitudinal directions. The subscript indicates the order of appearance for modes that share the same number of antinodes. For example, monopole modes $T(1,1)_x$ are known to be efficient radiators of sound; transversal dipoles $T(2,1)$ usually provide more sound pressure to the sides, giving a “monitor effect” to the player while other multipole modes contribute to sound.
projection by modulating the sound waves phase in three dimensions in front of the instruments (Gore & Gilet 2011). To understand the mandolin’s acoustic response, it is important to determine which eigenmode shapes correspond to the signature mode peaks. Therefore, to this end, we highlighted the eigenmode nodal lines using Chladni patterns (as detailed in the Materials and Methods section). The results are shown in Fig. 7 for the mandolin WWDF-1. Table 2 summarizes the results of the peak assignments for the various mandolins. Finally, we also included three mandolins built by the same luthier (Federico Gabrielli) that share the same geometry as mandolin WWDF-1.

By analyzing the signature modes of mandolins, we were able to identify some important features of the acoustic response of these instruments. In particular, the lowest resonance peak at approximately 200 Hz, called \( T(1,1)_r \), is a characteristic of every mandolin and is related to the Helmholtz resonance of the air cavity. By comparing the admittance to the sound pressure level (SPL), it can be observed that this eigenmode has a low intensity in the admittance curves. This means that the coupling between the Helmholtz resonance of the box and the soundboard is relatively weak. This behavior is very different from that of guitars and violins (Hess 2013), as well as from other types of mandolins,
Figure 7: Top: Sound radiation spectrum of mandolin WWDF-1 with identified eigenmodes. Bottom: drawing of the nodal lines of the first 5 eigenmodes found using Chladni patterns technique.

Table 2: Frequencies of the first three eigenmodes ($T_{(1,1)_1}$, $T_{(1,1)_2}$, and $T_{(1,2)}$) of different mandolins

| Mandolin                   | $T_{(1,1)_1}$ (Hz) | $T_{(1,1)_2}$ (Hz) | $T_{(1,2)}$ (Hz) |
|----------------------------|--------------------|--------------------|-----------------|
| Monzino 1908               | 180.3              | 451.5              | 545.1           |
| De Cristofaro 1906         | 169.6              | 483.8              | 815.6           |
| Anonymous beg. XX cent.    | 204.3              | 530.9              | 1035            |
| WWDF-1 (Gabrielli model)   | 198.2              | 588.3              | 746.1           |
| Gabrielli 2016             | 208.9              | 471.4              | 508.4           |
| Gabrielli 2018             | 197.5              | 632.2              | 689.4           |
| Gabrielli 2014             | 199.9              | 694.5              | 844.2           |
| Average (RSD%) all mandolins | 194.1 (7.2)         | 553.6 (17.9)       | 740.5 (24.5)    |
| Average (RSD%) Gabrielli mandolins | 201.1 (2.6) | 596.6 (15.8) | 697.0 (20.2) |

In the last two rows, the average frequency and the relative standard deviation (RSD, expressed in percentage) are shown for all mandolins and for the four mandolins sharing the same geometry (Gabrielli model). RSD is the relative standard deviation.
such as bluegrass instruments (Cohen & Rossing 2003). Furthermore, this feature was also observed by measuring the sound spectrum after hindering the Helmholtz resonance — and hence, the coupling with the soundboard — by plugging the sound hole. Notably, only a very small (<1 Hz) frequency shift was observed for the $T_{1,1,2}$ mode for most mandolins. This can be attributed to the high stiffness required to withstand the static force of the eight strings, which is a characteristic of the modern mandolin, which makes its structure much more stressed than other stringed instruments. At higher frequencies, within the signature modes, the subsequent peak, $T_{1,1,2}$, is related to the first eigenmode of the soundboard and is typically located between 450 and 700 Hz. These two peaks, $T_{1,1,2}$ and $T_{1,1,2}$, are characteristic features of mandolins; moreover, with particular regard to the first one, they do not vary much in frequency between the instruments we have analyzed. Subsequent peaks at higher frequencies are related to higher-order soundboard modes such as the longitudinal dipole $T_{1,1,2}$ (see details in the next section), the transverse dipole $T_{2,1}$, etc. At frequencies higher than approximately 2 kHz, the peaks become very close to each other and can no longer be distinguished, resulting in a relatively even acoustic response.

3.1.3 Soundboard Geometry and Characteristic Eigenmodes Order

As previously reported, the monopole-type radiation from modes $T_{1,1,1}$ and $T_{1,1,2}$ and mode ordering is quite standardized across several types of classical mandolins. Similar to guitars and other musical instruments, this characteristic formant (Woodhouse 2021) contributes to defining the particular mandolin sound timbre. This feature can be addressed to the particular ladder bracing of the mandolin soundboard; specifically, a configuration inherited from past lutes that, together with the horizontal bend, serves the purpose of stiffening the region close to the bridge to withstand the string static forces (Woll 2021). Figure 8 shows the inside of the soundboard of some historical mandolins. All these soundboards show a similar type of ladder spanning more than two centuries. This geometry provides a large transversal stiffness (more details in Section 3.2.2) and is also responsible for the appearance of mode $T_{1,2}$ (long dipole) at lower frequencies with respect to mode $T_{2,1}$ (cross dipole), as opposed to what happens in guitars. Likewise, mode $T_{1,3}$ (long tripole) occurs at a lower frequency with respect to $T_{3,1}$ (cross tripole). In this regard, mandolins show vibrational behavior that is more similar to that of lutes (Rossing 2010).

3.1.4 Influence of the Bowlback

Another interesting feature of mandolins is that no peaks related to back vibration appear in the sound spectrum. This aspect, which mandolins share with
other bowlback instruments, can be ascribed to the high stiffness of the bowlback. This part is composed of several bent ribs and, although their thickness is relatively small (approximately 2 mm), the large curvature makes it a very stiff structure — that is, a shell. For this reason, bowlback eigenmodes have much higher frequencies with respect to those of the soundboard and generally do not couple with them. This characteristic makes mandolins very different from other instruments such as guitars or violins that often show a so-called live back (i.e., a back of which its vibration is coupled to that of the soundboard) and therefore contributes to the sound (Gore & Gilet 2011).

3.2 Influence of the Wood Properties

From the information gathered during the acoustic characterization of mandolins (see Table 2), it is clear that, although different mandolins are built in a similar fashion — typically using the same wood for the soundboard — there is a large variability between their acoustic properties. Moreover, mandolins built by the same builder that share the same material and geometry (see Gabrielli mandolins in Table 2) show a large variability. Since the instrument geometry is nominally the same, this variability can be ascribed to the variability of the wood properties, which can be very large even within the same wood species (Gore 2011). It is therefore interesting to understand the influence of wood properties variability on the vibrational properties of the mandolin soundboard. To this end, we performed FEA simulations using the COMSOL Multiphysics software, modifying the wood properties, and thereby evaluating the effect on the vibrational behavior of the soundboard. The frequency response of orthotropic plates, such as wooden soundboards, is particularly
affected by (1) the geometry (length, width, and thickness); (2) the elastic properties; and (3) the density of the material (Leissa & Qatu 2011).

3.2.1 3D soundboard model and FEA Validation
To perform simulations, we made a 3D drawing of the soundboard with the same geometry as the mandolin built during the project (Fig. 9). This geometry is also shared by the other Gabrielli mandolins reported in Table 2. To perform the FEA without increasing the computational and physical complexity, we simulated only the soundboard, neglecting the interactions with the air and the body of the instrument. In particular, the soundboard edges were constrained so that no movement was allowed in any direction (clamped edge condition). This simplification is justified by: (1) the weak coupling between the stiff soundboard and the air modes and (2) the relatively high mass and stiffness of the mandolin bowlback with respect to the soundboard. To validate the soundboard FEA, we calculated the first five eigenmodes reported in Fig. 10. The predicted results are quite accurate, as can be seen by comparing the frequencies and modal shapes as reported in Figs 7 and 10. The good agreement

![Figure 9](image1)
**Figure 9** Drawing of the mandolin soundboard. Soundboard thickness is 3 mm, reinforcing bars are 8 × 20 mm (width × height)

![Figure 10](image2)
**Figure 10** First five eigenmodes of the mandolin soundboard simulated with FEA

\[
\begin{align*}
T(1,1) &= 591 \text{ Hz} \\
T(1,2) &= 793 \text{ Hz} \\
T(2,1) &= 862 \text{ Hz} \\
T(1,3) &= 992 \text{ Hz} \\
T(3,1) &= 1140 \text{ Hz}
\end{align*}
\]
between the measurements and simulations shows that FEA simulations can be used to reliably predict the vibrational behavior of mandolins.

3.2.2 Variation of the Wood Elastic Properties
To understand the role of the wood properties, we first focused on the elastic properties variation, keeping the density and the plate geometry constant. This simplification allowed us to clarify the role of the wood properties on the acoustics of the instruments by isolating it from other parameters. To make the simulations more general, we considered “standard” European spruce properties of 10 GPa, 1 GPa and 1 GPa for $E_L$, $E_R$ and $G_{LR}$, respectively. Accordingly, Figure 11 shows the frequency variation of the first five modes by varying the elastic moduli $E_L$, $E_R$ and $G_{LR}$ of ±50% one at a time with respect to their nominal values. These results clearly indicate that the longitudinal elastic modulus plays a fundamental role in determining the frequency response of the mandolin soundboard. The transverse and torsional elastic moduli $E_R$ and $G_{LR}$ play a less important role, even in those modes where deformations are mainly transversal, such as in the case of mode $T(1,2)$ (cross dipole). This fact can be ascribed to the soundboard geometry with transverse braces, as their stiffness tends to prevail with respect to the low transverse stiffness of the soundboard. For an indicative comparison, by considering a ratio between the elastic moduli $E_L$ and $E_R$ of 10:1 and the typical geometry of the soundboard, the bending stiffness of the central part of the soundboard (between the central brace and the lower bout) is approximately 15 times lower than that of the lower transversal brace itself. Again, this is a distinctive feature of mandolins with respect to different instruments that do not have such transversal stiffness, such as violins or classical guitars (Jansson 2002).

**Figure 11** Left: frequency variation of the first 5 modes of vibration of a mandolin soundboard with respect to ±50% elastic properties variation, right: relative variation of the monopole frequency.
3.2.3 Variation of Wood Density

Wood density is another important parameter that affects the vibrational behavior of a soundboard. Because the elastic properties are statistically related to the wood density, we included this relation in the FEA. In particular, we referred to the data acquired during our previous wood characterization campaign (Quintavalla et al. 2022). The relation between the density and elastic moduli is reported in the Materials and Methods section. Simulations were run by varying the density from 300 to 450 kg/m³, a range representing the typical variability of selected European spruce used for musical instrument construction, according to our previous study (average density 374.6 kg/m³). From this analysis, we computed the eigenmode frequencies and modal masses — that is, the mass associated with each eigenmode — and the results are presented in Fig. 12. It is interesting to note that the variation in wood density leads to a notable change in the eigenmode frequencies, likely resulting in a different formant and sound. As an example, a variation of 106.1 Hz (from 488.1 to 594.2 Hz) occurs in mode $T(1,1)_2$, which corresponds to 3.4 semitones. Despite the increase in density leading to an increased soundboard mass, the modal frequency also increased, indicating that the stiffness increased more than the mass with density. Referring to Gore and Gilet (2011), from modal frequencies $f$ and modal masses $m$, by assuming that each mode behaves as a simple harmonic oscillator, it is possible to retrieve the modal elastic constants $k$ and, from which the mobility $M$, a quantity related to the eigenmode admittance that can be expressed as:

$$M = \frac{1}{\sqrt{km}}$$

Monopole $T(1,1)_2$ radiation is one of the most important factors for the acoustic response of the mandolin, as it is related to the perception of loudness. We

![Figure 12](image-url)
reported its variation as a function of density, as shown in Fig. 13. It is interesting to note that by keeping the soundboard thickness constant, the monopole mobility decreases if the wood density is increased. Although this is not surprising, it is worth noting that a large variation of mobility — in this case, 21.4% from 300 to 450 kg/m\(^3\) — is also expected if the density varies within the studied range. In this regard, this study provides an interesting interpretation of the mandolin acoustic response variability, both in tone and loudness, if the instruments are built following traditional rules where the soundboard geometry is kept constant.

4 Conclusions

In this study, we investigated the acoustical properties of modern Italian bowl-back mandolins. In particular, we highlighted some distinctive features in their sound spectrum and soundboard admittance. Similarly to guitars, two monopole modes occurred at low frequencies. These were followed by a longitudinal dipole mode, a characteristic similar to that of lutes, which is due to the particular type of bracing. This particular mode ordering is a consequence of the stiffness required to withstand the large static load of the strings. By means of the FEA, we determined the influence of wood properties on the acoustic response of the instrument. Particularly, the longitudinal elastic modulus of wood has a major effect compared to the radial and torsional moduli. Moreover, wood density also has a significant impact on both the eigenmode frequency and monopole mobility. As a consequence, the choice of wood used to realize the soundboard has a significant effect on the tone and loudness of the instruments.
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