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# Evaluation of Some Species of Faster Growing Woods Compared to Traditional Woods for Possible Use in Good Quality Musical Instruments

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**Abstract:** The guitar was chosen as a model for this research due to its shape and dimensions, which are characteristic of the acoustic body and can produce high, medium, and low frequencies. Spruce is considered the quality standard for the harmonic top, while a wood popularly known as Jacarandá is considered the quality standard for the bottom of the instruments. Considering the inadequate exploitation of jacaranda and the high costs of these types of woods, two forest species were evaluated to replace spruce (Marupá and Araucária) and two species to replace jacaranda (Andiroba and Jenipapo). Besides determining some physical properties and chemical analysis, elastic modulus, shear modulus, sonic impedance, and damping coefficient by sound irradiation, a methodology was developed where a comparative analysis of the woods was made through impulse excitation measurements and signal analysis. A view to compare the woods used for the soundboard and acoustic box of the guitar in the back of the guitar graphically or by the method of absolute differences between the properties or characteristics of the studied woods revealed that Marupá species is the closest wood to spruce Norway and Andiroba is the most similar wood to Jacarandá used for the back bottom of the guitar.

**Keywords:** Brazilian woods; classical guitar; musical instrument; Brazilian rosewood; physical properties; acoustic properties.



## 1. Introduction

Music is an important part of children's education because it improves sensibility, often feeds the soul, and helps to develop intellectual skills. Sound may be a personal preference. Some people prefer instruments with a more strident sound, while others prefer more velvety or clear notes. Despite personal preferences, different woods have a crucial effect on the sound generated by the instrument. Accordingly, this study is taken up to evaluate some wood species grown in Brazil with the aim of replacing the expensive imported wood named Norway spruce (Picea abies) used in good quality classical guitars soundboard and the rare wood named Brazilian rosewood (Jacarandá or Dalbergia nigra) used in the back body and sides of the string instrument. There are numerous types of wood used for bottom (back) and side sets. This is due to the fact that the traditional wood Jacarandá is expensive and in short supply [1-3]. The wood selection could be based on the measurement of density and elastic modulus, as shown in studies by Quintavalla, where the radial cut of the pieces was applied [4].

Normally, string instruments such as guitars are made of these two kinds of wood: spruce and rosewood [1], but it is of utmost importance to replace them with local woods available in large numbers in order to allow more people to enjoy the benefits of good quality string instruments. Studies related to alternate woods to replace standard woods for the reasons mentioned above have normally characterized these alternate woods for some properties and compared them with those of the traditional woods mentioned above. This is due to possible estimation of the acoustical behavior based on the values of the density (ρ) and the velocity of propagation (c), both of them being related through the coefficient of sound radiation[ $R = c/\rho$)] besides knowing the damping coefficient of these materials [5].

Figure 1 shows the model of the classical guitar of the Spanish Luthier Antônio Jurado Torres, which was used in this work and made available by the technology course in the construction of musical instruments of the authors' university-viz., Federal University of Parana (UFPR), Curitiba, Brazil.

The density of the material, the thickness of the soundboard plates, as well as the orientation characteristics of the fibers and the shapes of the wood affect the mechanical and vibratory behavior of the guitar [6].

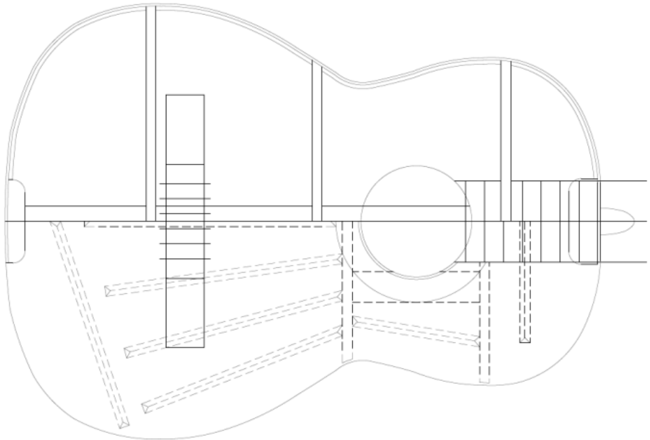


**Figure 1.** Classical guitar model.

Considering the climate change affecting traditional woods' growth and the world's wide variety of wood species still available, Norway spruce and Brazilian rosewood may be replaced to build good quality guitars if a fine selection of woods is made [7]. Sustainable forests may be incentivized; one example is sustainable Turkiye's forest practices and addressing the impact of plastic waste on forests and the environment [8]. The widespread presence of microplastic also has deleterious effects on the ecosystem and forests [9].

The functions of the loudspeaker may be viewed as a coupled oscillator system. The soundboard receives the impulse of the strings, which radiate through the resonance box, transmitting a certain frequency which, when propagating in the volume of air that exists inside the speaker and through the sides, oscillates with the bottom of the speaker. Therefore, the width of the sides influences the air volume of the speaker and, consequently, the timbre of the instrument. American Acoustic Standard (ASA) defines 'timbre' as "that property of auditory sense in terms of which the listener can judge that two sounds similarly presented, but having the same intensity and height are dissimilar" [10]. When the string of the instrument is touched, the resonance box is excited as a whole, but the background vibration amplitude is lower than the one in the soundboard, and it is still lower in the sidebands.

Due to population growth and the disorderly exploitation of forests, there has been an increase in deforestation, the main suppliers of tropical hardwoods for musical instruments, such as Brazil, India and African countries, have reduced their stocks and consequently there has been an increase in prices and greater difficulty in finding certified wood, certainly due to the slow vegetative growth of these species. The replacement of these woods by other woods is done through studies that indicate other wood species and other types of substitutes such as polymer composites reinforced with synthetic and natural fibers [11].

The velocity of sound in wood means the speed at which wood transmits received energy. Wood with a high sound velocity and low internal damping facilitates the best transmission of vibrational energy [12].

Tropical woods such as Brazilian rosewood, Indian rosewood, and black ebony are considered Class A woods for use in the soundboard and other parts of musical instruments [13].

Jacarandá of Bahia, internationally known as Brazilian rosewood, which is used for the back of classical guitars and has been known commercially for more than 300 years, has been in danger of extinction in Brazil since 2008.

Considering the importance of music in children and the development of sensibility and of human beings in general, it is essential to find alternative woods for use in good-quality classical guitars. However, the main problem with the traditional use of wood in musical instruments is related to their slow growth and high cost. Therefore, it is necessary to evaluate alternative woods that can be used in the construction of instruments presenting high quality, given the imminent demand for musical instruments and the benefits they may bring to society. It may also be noted that over a long time, the selection of wood for use in musical instruments has been made according to the trial and error method. In present times, one can use a more scientific approach in choosing species of wood more appropriate for different musical instruments.

A detailed study was undertaken, which is described in this paper. Four types of alternative Brazilian woods selected are Marupá (Simarouba amara Aublet) and Araucária (Araucaria angustifolia) for the soundboard, needs low-density woods. Further, considering the facts mentioned above regarding Jacarandá, two other wood species of Brazil, viz., Andiroba (Carapa Guyanese) and Jenipapo (Genipa Americana), were evaluated for their use for the back of the classical guitar as this part should be made of higher densities woods. The selection of Andiroba wood is due to its use in the cosmetics market. It is a source of income for a large part of the Brazilian Amazonian population and thus will hardly enter the list of endangered species. The second wood species, Jenipapo, is another Brazilian wood selected for this study because it has a vegetative growth that is considered fast, and its wood is easy to mold. Considering the background mentioned above, in this work, these woods are used in the back of the acoustic guitar speaker, which is then reinforced to increase the gluing surface since the thickness of the blades is approximately 2 mm.

Finally, flexible plywood was selected because it is widely used in industries that make low-cost musical instruments despite its known demerits, such as damping and efficiency being quite inferior to solid wood. These limit the reflection and propagation of the sound waves while going out through the sound hole of the instrument that is located on the soundboard. On the other hand, plywood does not show much variation with the humidity and is a standardized material that can define the style of a brand. The use of solid wood in a guitar always results in better sounds as it improves with age, but it is affected by humidity and often is much more expensive than plywood.

Further, it is well known that the characteristic sound is, in part, a function of the speed of sound in a particular material, which is directly proportional to the stiffness of the material and inversely proportional to its density. The mass of a plate, like an instrument soundboard, is a function of its thickness and density. Therefore, stringed instrument soundboards are made as thin as possible--only thick enough to withstand the loads imparted to the soundboard without excessive deflection or structural failure. Material strength and stiffness are the primary parameters affecting the minimum soundboard thickness for a given material. Therefore, to achieve minimum mass, strength, stiffness, and density, all must be considered in material selection. Since higher strength and stiffness are better, and lower density is better, and all have first-order effects, a simple ratio with strength or specific stiffness in the numerator and density in the denominator is a good relative measure of a material's potential as a soundboard. This ratio, called specific strength or specific stiffness, has long been recognized by luthiers (stringed instrument builders), who have used this parameter to select woods. Comparing materials in specific applications requires a methodology that eliminates the various variables that allow evaluating the change in the material to be studied or compared as a quality reference, according to instruction [14]. It is, therefore, necessary to evaluate these properties of the selected wood species in this study.

Thus, this study aims to evaluate some of the fast to moderate-growth woods regarding their potential to replace standard woods normally used in the manufacture of high-quality guitars, as mentioned above, and compare them with traditional wood species established by musicians and luthiers. For this purpose, an analysis of experimental signals from the harmonic soundboard and the acoustic box of the classical guitar was made, and the results were compared with the results obtained from the signal analysis through the physical and mechanical properties of these selected materials. Accordingly, in the following pages, details of woods selected with their characterization with respect to various properties that are required for their use in guitars as substitutes for traditional woods mentioned earlier are given. Obtained results of all these woods are then discussed and compared with those of traditional woods, and finally, conclusions based on these are presented. It is hoped that this study will stimulate other researchers to look into the woods available in their countries to replace the expensive traditional woods mentioned earlier.

## 2. Materials and Methods

*2.1. Materials.*

Table 1 lists the names of the woods used, the family to which they belong, and the name of the species for both the soundboard of the guitar (top) and back.

**Table 1.** Names of woods used, the family to which they belong, and the name of the species for both the soundboard of the guitar (top) and back.

| | **Popular name** | **Family** | **Specie** |
|---|---|---|---|
| Top of the Acoustic box | Abeto/Spruce | Pinaceae | Picea abies (L) Karst. |
| | Marupá | Simaroubaceae | Simarouba amara Aublet |
| | Araucaria | Araucariaceae | Araucária angustifolia (Bertoloni) Otto Kuntze |
| Background and Lateral side of the Acoustic box | Popular Name | Family: | Specie: |
| | Rosewood/Jacaranda da Bahia | Fabaceae (Leguminosae Papilionoideae) | Dalbergia nigra (Vellozo) Freire Allemão |
| | Andiroba | Meliaceae | Carapa guianensis Aubl. |
| | Jenipapo | Rubiaceae | Genipa americana Linnaeus |

Wood samples from two trees of Jenipapo and Jacaranda used in this study were purchased from the state of Bahia, Brazil. Two samples of each species were used. Samples 1 of these species were donated by the Federal University of the Recôncavo da Bahia in the city of Cruz das Almas, and samples 2 were purchased from the demolition timber trade in the city of Feira de Santana-Ba (Brazil). The species of Andiroba, Araucaria, and Marupá were obtained from different sources (Sovierzoski Madeiras and Madeireira Fridalina, one sample for each species), Curitiba (PR-Brazil). Imported Norway spruce (hereafter referred to as ‘spruce’ only) samples were purchased from two stores specializing in musical instruments in the city of São Paulo, Brazil. Also, Jacarandá wood was used as a side body for all the guitars that were built.

Figure 2. (a) shows various wood veneers used in this work for the soundboard. While Figure 2 (b) shows one sample of plywood and two samples each of Jacarandá, Andiroba, and Jenipapo, Figure 2(c) shows the four soundboards, made of plywood, Araucária, Norway spruce, and Marupá species, body backs with their reinforcements and the Jacarandá (Brazilian rosewood) for the lateral side of body of the guitar, all of which make up acoustic guitar ensemble.

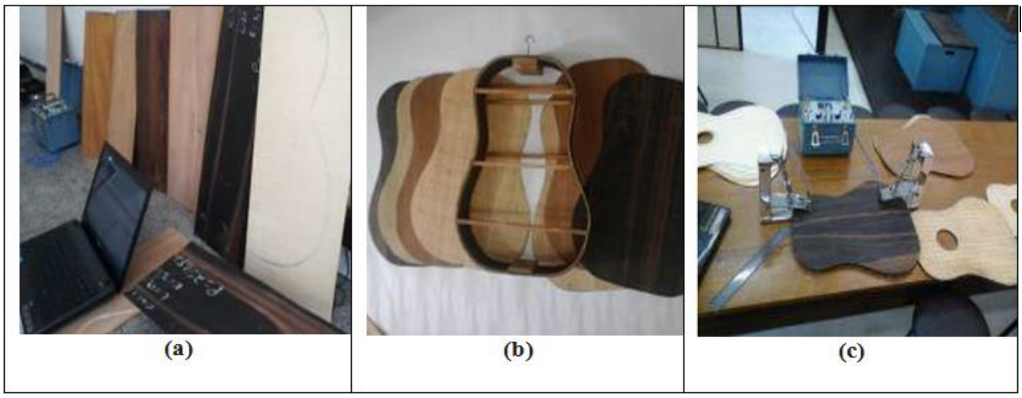



**Figure 2. (a)** Wood veneers used in this work; **(b)** Backs of the classical guitar body made of plywood, Jacarandá, Andiroba, or Jenipapo and its side made of Jacarandá; **(c)** Jacarandá side of the classical guitar, four soundboards made of plywood, Araucária, Norway spruce, and Marupá.

The Virola surinamensis wood was identified for both sides of the flexible laminar plywood used in this work and was obtained from Sovierzoski Madeiras, Curitiba (PR-Brazil).

All the wood samples used for the analysis of the harmonic soundboard of the guitar in this study had the same thickness as the soundboards, which was approx. 2.5 mm and the weight was approx. 0.12 kg. The samples on the bottom of the speaker had a thickness of 2mm and a weight of approximately 0.208 kg. All these samples were kept in a climatic chamber with 12% humidity for six months.

### *2.2. Methods.*

#### 2.2.1. Preparation of samples.

It is reported that the sound propagation speed in the longitudinal direction is one of the main variables to classify the quality classes of a material, followed in degree of importance by Poisson's ratio in the longitudinal-radial direction and the sound propagation speed in the longitudinal direction. Radial direction [15]. Still, when selecting a material, other variables, such as density, must also be taken into account. Despite this, this study developed a methodology where a comparative analysis of the selected woods was carried out on samples in the classical guitar shape through velocity measurements of wave propagation and modal analysis. With the objective of eliminating the maximum number of variables existing in the complex vibrational mechanical system of the guitar and in order to keep the volume of air constant in the acoustic body (speaker), the harmonic (soundboard and back) of the acoustic box of the guitar was investigated, without the presence of the guitar neck and headstock and using only one fixed Jacarandá side. Accordingly, among various variables in the acoustic guitar set, the type of wood, the model of the speaker, the types of reinforcement and fan, the surface coating, the thickness of the soundboard, and the humidity of the material can be mentioned. Of these, the velocity of wave propagation both in parallel and perpendicular directions to wood fibers, modulus of elasticity, shear modulus, damping, sound irradiance coefficient, sound impedance, and signal analysis for samples of the same thickness or same weight were evaluated for the three selected woods. For each characteristic or test performed, a comparison was made with Norway spruce, which is considered ideal for the guitar soundboard. Aiming to eliminate the undesirable variables in this study and to facilitate the analysis of the type of materials used, only one side was used with the cross pieces and reinforcements in the format of the classic guitar of the luthier Antônio Torres. These can be seen in Figures 2(b and c), which show the wood of the guitar soundboard and back and the side used as a template.

Tests were carried out through impulse excitation, and results were obtained, such as elastic modulus, shear modulus, sonic impedance, and sonic irradiation damping coefficient. The moisture content and density of the studied woods were also compared. The properties or characteristics of the woods were studied graphically.

Acoustic performance (volume, quality, and timbre) depends mainly on density, Young's modulus (E), and damping of material (η). Accordingly, following Wegst, the main variables used in the selection of instrument materials are the velocity of sound propagation in the material (v), impedance (z), sound radiation coefficient (R), and damping (η) [5].

After cutting to standard thicknesses of 2.5 mm, all wood pieces chosen for the study were conditioned in the scalable chamber with controlled humidity of 12% (Copant standard 460/2014), and they were taken to the Wood Technology Laboratory (Physical-Mechanical Properties), UFPR, Curitiba.

#### 2.2.2. Characterization.

##### 2.2.2.1. Density of wood species.

Twelve specimens of approximately 2 cm from each region, which had their mass determined on an Adventurer Ohaus precision balance, were chosen to determine bulk density. Then, using the Archimedes principle and with the aid of an apparatus that forced the specimens to be totally submerged, they were placed in a beaker with water to determine their volumes. Assuming that the density of water is 1000 kg $m^{-3}$, the indicated mass difference on the scale provided the displaced volume that corresponds to the sample volume.

##### 2.2.2.2. Determination of moisture of selected woods.

The moisture content of the wood samples was determined using the Heraeus drying oven according to the standard Copant 460 - Wood: methods of determination of density and humidity. The samples were weighed until the weight did not vary more than 0.5%. Then, after heating the samples at 100°C for 24-48h, the samples were taken out of the oven and placed in a desiccator to cool, followed by weighing the samples again. The moisture content of all the samples was then calculated by the difference in the weights of the fiber before and after drying.

2.2.2.3. Morphology and chemical analysis of wood species.

Morphology of selected wood samples was carried out using both optical and scanning electron microscopy techniques.

First, for the optical microscopic observation, a cross-section of all the samples was used with a 50x magnification in the Olympus CX 40 Microscope to obtain micrographs with a view to compare the micro pores in the species analyzed.

For the scanning electron microscopy studies, including elemental analysis of all the samples studied, samples were prepared of suitable sizes and then gold coated. These samples were then observed under the scanning electron microscope (SEM) (Make: TESCAN VEGA3 LMU) having energy dispersive system (EDS) chemical analysis system (OXIFORD) with AZ Tech (Advanced) software with 80 mm² SDD type detectors available at the Microscopy Center of UFPR were used to understand the morphology of the selected wood samples as well as to know chemical contents of these using emission Current = $60.733e^{-6}$ amps, voltage (HV) =30.000 and 3 volts. This equipment has a resolution of 3 nm and allows magnifications up to 300 kX, with controlled pressure between 3 and 500 Pa.

2.2.2.4. Determination of acoustic properties of wood species by impulse excitation technique.

In order to obtain the elastic and acoustic properties of the different wood species selected for this study, the impulse excitation technique, which is a non-destructive method, was used. It uses the natural vibration frequencies to determine the elastic modulus of regular geometry samples having dimensions 80 mm x 15 mm x 3 mm. Before going into details of measurements using this technique, some details about the technique are given below.

The impulse excitation technique is a vibration analysis of a sample where resonant frequencies are characterized in the test material, which is related to their rigidity, mass, and geometry, measuring the resonant frequency of appropriate geometry. Mechanical stimulation of samples with an impulse tool detects the mechanical vibrations resulting from the sample and converts them into electrical signals. The fundamental resonant frequencies in the sample dimensions and mass are used to calculate engineering constants. Accordingly, this technique consists essentially of determining the elastic moduli of a material from the natural frequencies of vibration of a regular geometry test specimen (bar, cylinder, disk, or ring). These frequencies are excited by a short-term mechanical impact, followed by the acquisition of the acoustic response by a sensor. The impulse excitation technique obtained the velocity of sound in parallel and perpendicular directions using a Sonelastic version 1.1 from ATCP company. Besides this, Metriguard Stress Wave Timer model 239A with the woods in the guitar shape and with the same thickness or weight was also used to determine the velocity of sound in the parallel direction. It may be noted that this equipment does not give the readings for perpendicular direction, and accordingly, only readings in the parallel direction were obtained, which were the same as those obtained using the impulse excitation technique.

The velocity that a sonorous signal propagates in the material's interior is an important acoustic parameter that can be obtained by an equation related to Young's modulus and wood density. Further, the propagation velocity of the sound wave in materials may vary according to several properties. In woods, this property varies according to species, as can be observed according to measurements taken in the sonelastic and stress wave timer.

The velocity of sound in the parallel direction was determined using the Sonelastic equipment, while the stress wave timer was used to determine the velocity of sound in parallel and perpendicular directions. The results of wave propagation velocity were similar in the two equipment, and therefore, the other tests were carried out only through the Sonelastic equipment. Details of these determinations are given below.

2.2.2.4.1. Velocity of sound.

The velocity of sound was determined using the ATCP brand Sonelastic rig. The samples were analyzed according to the aspect ratio following ASTM E1876-09 standard. Samples of two different trees were used for each species of wood analyzed. Details of the procedure followed are as follows: After measuring the dimensions and determining the mass, the samples were characterized by Sonelastic equipment through the flexural and torsional vibration modes. A mathematical treatment was used in the signal to obtain the frequency spectrum (fast Fourier transform). From this, the dynamic elastic modulus was calculated by considering the geometry, mass, dimensions of the specimen, and frequency obtained by the equipment. For the excitation of the desired vibration modes, certain boundary conditions must be imposed. The differences lie in the positioning of the acoustic pickup (microphone).

The main sound characteristics of the materials involved were obtained. The damping was calculated by analyzing the decay of the signal from a frequency band whose center is the natural frequency. The range that was adopted was +/- 500 Hz, i.e., if the resonance frequency was 2000 Hz, the range between 1500 Hz and 2500 Hz was analyzed.

Damping characterizes how fast the decay of a body's vibration amplitude will be after its mechanical excitation. This property is directly related to internal mechanisms of energy dissipation of the material, such as internal friction. Other damping parameters include the quality factor (Q), the logarithmic decay (σ), and the angle of loss (ψ). After the tests, the data was processed. From the values of apparent density and modulus of elasticity, the respective values for sound impedance (z), the velocity of sound (v), sound radiation coefficient (R), and (η) damping were obtained using equations 1, 2, 3 and 4 respectively, which are given below:

$$V = \sqrt{E/\rho} \qquad (1)$$

$$Z = V.\rho = \sqrt{E.\rho} \qquad (2)$$

$$R = V/\rho\sqrt{E/\rho^3} \qquad (3)$$

$$\eta = 1/Q = \tan\Psi = \delta/\Pi \qquad (4)$$

It may be noted that equation 3 relates the sound radiation coefficient to the velocity of propagation of the sound signal and the density [16], while equation 4 relates the damping with the quality factor, the logarithmic decay, or the angle of loss. The sound radiation coefficient describes how much vibratory energy will be converted into noise. Suppose it is desired that the sound emitted by an instrument be of high volume (intensity). In that case, it is necessary that the material shows a high value for this coefficient (for example, xylophones).

2.2.2.4.2. Sound velocity propagation.

The velocity of wave propagation of wood in the classic guitar format was determined using a set of clamps, a pendulum, and a sphere to excite voltage waves. For this purpose, a Stress Wave timer (Metriguard makes; Model 239A→ Available at Wood Technology Laboratory - Physical and Mechanical Properties, UFPR, Curitiba, Brazil) was used. The clamps were fixed at a distance of 300 mm in all samples. Figure 2c shows the arrangement for the analysis of the velocity of sound propagation at the top and back of a classical guitar. The analysis was initiated when the first voltage wave was excited and ended when the wave reached the accelerometer. The propagation time was displayed in microseconds. The propagation velocity of the sound wave in materials may vary according to several properties. Accordingly, this property varies in wood according to species, type of cut, moisture content, and, mainly, the presence of knots.

In order to obtain a numerical criterion and not just a visual comparison of the properties, the absolute differences method was used to compare all the properties of the wood considered to be ideal and the woods proposed for a probable replacement. Equation 5 was used to obtain each property or characteristic of the selected woods.

$$\frac{(Property\_of\_studied\_wood) - (Property\_of\_reference\_wood)}{(Property\_of\_reference\_wood)} \quad (5)$$

2.2.2.4.3. Signal Analysis of wood species.

The signal analysis provides a set of parameters that characterize the dynamic behavior of a system structure in the form of natural frequencies, damping factors, and natural modes of vibration.

Considering the guitar as a vibrational mechanical system (VMS), a model of analysis was developed whose objective was to evaluate the sound characteristics of the wood and, consequently, due to its substitution of forest species, to characterize the best materials for the harmonic top of the guitar. This method consisted of using the same side of the guitar to analyze various configurations of wood on the top.

With this information, a mathematical model can be formulated for its dynamic behavior. The mathematical model formulated is called the 'signal model' of the system, and the information for the characteristics is known as 'modal parameters'. Thus, the experimental modal analysis in the plywood and woods used in this study simulated the degrees of freedom of the classical guitar soundboards and was carried out with the use of the program LMS Test.mLab, interface Impact Test version 13.1 to connect and calibrate the driver (Impact hammer, sensitivity of 2 mV/N(tension/force) and the receiver accelerometer, sensitivity 9.79 mV/g (tension/acceleration). The equipment was built by Brüel and Kjaer, and sensitivities were used according to the builder's standards. Firstly, a structural mesh was built in Cartesian format for the harmonic soundboard of the classical guitar with geometrically corresponding distancing patterns with the structural mesh of the LMS Test. Figure 3 shows the structural mesh used for the learning management system (LMS software) test. According to this figure, measurements were made in a structural mesh with a distance of 20 mm between the points of measurement in the vibrational analysis, with a total of 336 points in the structural mesh of the harmonic soundboard and a total of 352 points in the structural mesh of the guitar body back. Through the Fourier analysis, it is possible to identify harmonics present in a sound wave.

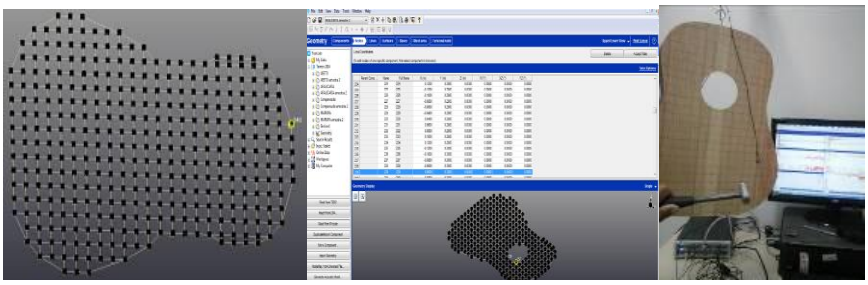


**Figure 3.** Structural mesh of the LMS test.

These signals were used to obtain the frequency response function (FRF: Relationship between the vibrational response at a location and the excitation) and then the natural modes, natural frequencies, and damping for each frequency of the set of woods in the surveyed instruments.

In the case of the backside, through the Fourier analysis, one can identify the harmonics present in a sound wave, and from these, resulting sounds can be compared, and desirable ones can be identified from any sound source. Using programs with the tools of finite analysis method, modal analysis, and Fourier transform, it has been possible to obtain the vibrational behavior of a material and a spectrum of a sound wave or harmonic series and thus analyze its characteristics. The conversion of a time signal to the frequency domain is obtained using the Fourier transform, as shown in equation 6.

$$F(\varpi) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \qquad (6)$$

## 3. Results and Discussion

*3.1. Analysis of wood species used.*

3.1.1. Density and moisture content.

Table 2 shows the obtained density and moisture content values of all 4 wood samples, viz., Araucaria, Marupá, Andiroba, Jenipapo, Spruce, and rosewood, used in making soundboards and back bodies of guitars. It may be noted that one sample of each wood was cut from two different trees. It can be seen from the table that the Araucaria species has moisture content closer to that of the Norway spruce but not to that of the Marupá species, while the density of the Marupá species is closer to that of the Norway spruce. On the other hand, the Rosewood sample shows the highest density value among the three species (used for the side body of all guitars and also for one back body) studied, followed by Andiroba, the latter also showing the highest moisture content.

**Table 2.** Moisture and density of wood species used in the guitar soundboards and back bodies.

| Species to back | Apparent specific Mass (Kg.m$^{-3}$) | Moisture content (%) | Species to top | Apparent specific Mass (Kg.m$^{-3}$) | Moisture content (%) |
|---|---|---|---|---|---|
| Brazilian rosewood 1 | 0.911 | 10.539 | Norway spruce 1 | 0.43 | 14.423 |
| Brazilian rosewood 2 | 0.773 | 9.781 | Norway spruce 2 | 0.425 | 14.474 |
| Andiroba 1 | 0.679 | 15.371 | Araucaria 1 | 0.559 | 14.491 |
| Andiroba 2 | 0.728 | 15.436 | Araucaria 2 | 0.635 | 14.65 |
| Jenipapo 1 | 0.661 | 15.563 | Marupá 1 | 0.483 | 13.313 |
| Jenipapo 2 | 0.735 | 13.555 | Marupá 2 | 0.482 | 14.42 |

The Marupá showed an apparent specific mass, which is considered low (0.48 g cm$^{-3}$), while the Andiroba is classified as high (0.72 g cm$^{-3}$), although this value is lower than rosewood. Following Kitto, Brazilian Rosewood and Norway Spruce's densities were determined as 0.835 g cm$^{-3}$ and 0.460 g cm$^{-3}$, respectively [17].

3.1.2. Morphology study of the three wood species.

Figure 4 (a-f) shows optical micrographs of the surface of samples of Araucária, Marupá, Norway spruce, Jenipapo, Andiroba, and Rosewood, respectively, while Figures 5 (a-f) shows the same as observed under the scanning electron microscope of same species respectively. It should be noted that the spruce and the Araucária species belong to a temperate climate, while the Marupá species belong to a tropical climate. Andiroba and Jenipapo can be classified as having fast growth compared with Brazilian rosewood. With this background, observed morphologies are explained as follows:

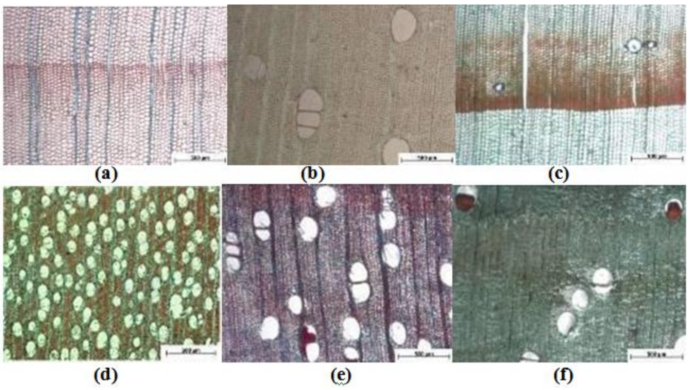


**Figure 4.** Optical micrographs of wood species studied: **(a)** Araucária; **(b)** Marupá; **(c)** Norway spruce; **(d)-** Jenipapo; **(e)**- Andiroba; **(f)** Brazilian rosewood [Mag: 50x ].

The study by Shirmohammadi *et al*. [18] shows the relationship of anatomy, internal friction, and elastic modulus in a comparison between species affect the sound quality of the material.

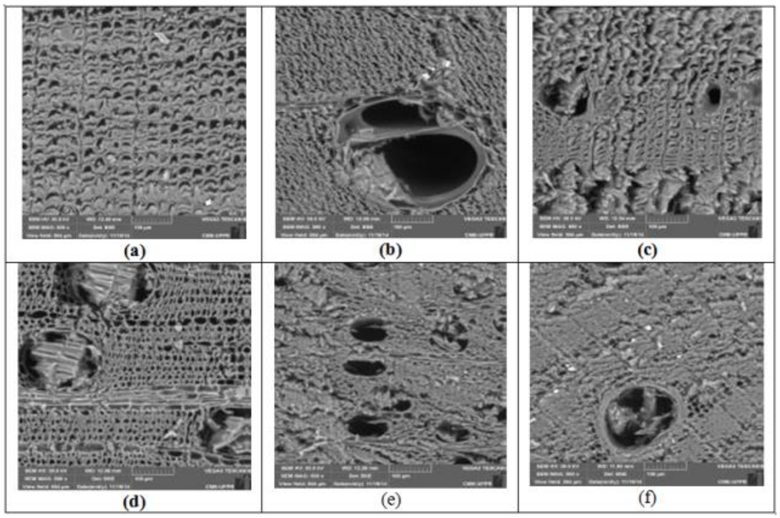


**Figure 5.** Scanning electron micrographs of wood species studied: **(a)** Araucária; **(b)** Marupá; **(c)** Norway Spruce; **(d)**-Jenipapo; **(e)**- Andiroba; **(f)** Brazilian rosewood.

From Figures 4 (a and c) and Figures 5 (a and c), it can be seen that Araucaria and Norway spruce species, being resinous forest species, show the presence of resinous channels. Araucaria is a wood with longitudinal tracheids characterized by latewood, also called 'summer wood' (less dense due to larger cells and thinner walls at later stages, while it is the reverse in the early season stage). The latewood presents thicker cells delimiting the ring of growth and small resinous canals. On the other hand, from Figure 4 (b) and Figure 5 (b), it can be seen that the Marupá species, a tree considered to be a hardwood variety (usually found in broad-leaved temperate and tropical forests with most deciduous form in temperate and boreal latitudes, while they are mostly evergreen in tropics and subtropics), has diffuse porosity. The Marupá is a species that possesses the right grain and fine texture, as well as solitary, double, and triple pots. Accordingly, it exhibits narrow and numerous rays (Figures 4b and 5b). This is different from spruce and Araucaria species, which exhibit a layer of indistinct growth. It can be observed that the Araucaria species has more homogeneous porosity and, therefore, it is a wood of higher density, as seen in Table 2.

Further, the Jenipapo is a more porous wood exhibiting diffuse porosity (having vessels more or less evenly distributed throughout an annual ring and not varying greatly in size) with many solitary pores, which in general are not in contact with other numerous pores [Figure 4 (d) and 5 (d)].

On the other hand, Andiroba is a species that shows solitary and geminate vessels, predominantly empty, some with contents, and presents a diffuse porosity and distinct growth layer [Figure 4 (e) and 5 (e)]. Andiroba is more similar to the jacaranda because it presents double and obstructed vessels (tylose). The number of vessels and their sizes determine the density. Finally, the Brazilian rosewood (Jacarandá) is a wood characterized by presenting a few solitary pores, which can be geminated and may have twinned pores [Figure 4 (f) and 5(f)]. Visual inspection of optical and SEM micrographs shown in Figures 4 (a-f) and 5 (a-f) indicates that Marupá is more similar to Norway Spruce than Araucaria and that Andiroba is more similar to Brazilian rosewood than Jenipapo.

#### 3.1.3. Chemical analysis of three wood species.

The energy dispersive X-ray analysis (EDS) showed chemical elements present in the different woods studied. Table 3 shows the chemical analysis of spruce, Marupá, and Araucaria samples obtained by EDS. It can be seen that the potassium and calcium content of the spruce is 0.02 % w / w and 0.03% w/w in the samples of the two different trees analyzed and that the content of these elements in Araucaria and Marupá was higher. In addition, Norway spruce does not contain silicon, sulfur, chlorine, or iron in its composition, unlike Araucaria, which is the only wood that shows silicon. This may suggest that this sample would have been contaminated with sand.

**Table 3.a.** The content of chemical elements was found in Norway spruce, Araucaria, and Marupá samples.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Norway spruce 1** | Elements | C | O | K | Ca | Total | | | | |
| | % p/p | 57.91 | 41.96 | 0.04 | 0.08 | 100.00 | | | | |
| | %Atômic | 64.74 | 35.21 | 0.02 | 0.03 | 100.00 | | | | |
| **Norway spruce 2** | Elements | C | O | K | Ca | Total | | | | |
| | % p/p | 58.52 | 41.33 | 0.06 | 0.09 | 100.00 | | | | |
| | %Atômic | 65.32 | 34.63 | 0.02 | 0.03 | 100.00 | | | | |
| **Araucária 1** | Elements | C | O | Si | S | Cl | K | Ca | Fe | Total |
| | % p/p | 58.85 | 40.81 | 0.03 | 0.02 | 0.08 | 0.11 | 0.05 | 0.04 | 100.00 |
| | %Atômic | 65.69 | 34.20 | 0.01 | 0.01 | 0.03 | 0.04 | 0.02 | 0.01 | 100.00 |
| **Araucária 2** | Elements | C | O | S | Cl | K | Ca | Fe | Total | |
| | % p/p | 59.42 | 40.16 | 0.01 | 0.04 | 0.27 | 0.08 | 0.01 | 100.00 | |
| | %Atômic | 66.25 | 33.61 | 0.00 | 0.02 | 0.09 | 0.03 | 0.00 | 100.00 | |
| **Marupá 1** | Elements | C | O | S | Cl | K | Ca | Total | | |
| | % p/p | 59.15 | 40.53 | 0.02 | 0.07 | 0.16 | 0.08 | 100.00 | | |
| | %Atômic | 65.96 | 33.93 | 0.01 | 0.02 | 0.06 | 0.03 | 100.00 | | |
| **Marupá 2** | Elements | C | O | S | Cl | K | Ca | Fe | Total | |
| | % p/p | 58.55 | 41.18 | 0.02 | 0.01 | 0.08 | 0.15 | 0.01 | 100.00 | |
| | %Atômic | 65.39 | 34.52 | 0.01 | 0.00 | 0.03 | 0.05 | 0.00 | 100.00 | |

Samples of Marupá also show low levels of sulfur, chlorine, and iron. It may also be noted that as two samples of each wood species were taken from different trees and analyzed, it is difficult to have a representative number for the content of elements as the age and soils where the trees were cut could be different.

**Table 3. b.** Contents of chemical elements found in samples of Rosewood, Andiroba, and Jenipapo species.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Brasilian rosewood 1** | Elements | C | O | S | Cl | K | Ca | Total | |
| | % p/p | 64.40 | 35.40 | 0.07 | 0.01 | 0.02 | 0.09 | 100.00 | |
| | %Atômic | 70.74 | 29.19 | 0.03 | 0.00 | 0.01 | 0.03 | 100.00 | |
| **Brasilian rosewood 2** | Elements | C | O | Na | S | Cl | K | Ca | Total |
| | % p/p | 61.49 | 37.20 | 0.46 | 0.03 | 0.41 | 0.18 | 0.23 | 100.00 |
| | %Atômic | 68.37 | 31.05 | 0.27 | 0.01 | 0.15 | 0.06 | 0.08 | 100.00 |
| **Andiroba 1** | Elements | C | O | Cl | K | Ca | Total | | |
| | % p/p | 59.46 | 40.47 | 0.01 | 0.01 | 0.05 | 100.00 | | |
| | %Atômic | 66.17 | 33.81 | 0.01 | 0.00 | 0.02 | 100.00 | | |
| **Andiroba 2** | Elements | C | O | S | Cl | K | Ca | Total | |
| | % p/p | 59.72 | 40.12 | 0.01 | 0.02 | 0.02 | 0.11 | 100.00 | |
| | %Atômic | 66.44 | 33.51 | 0.00 | 0.01 | 0.01 | 0.04 | 100.00 | |
| **Jenipapo 1** | Elements | C | O | S | K | Ca | Total | | |
| | % p/p | 57.83 | 42.04 | 0.01 | 0.06 | 0.05 | 100.00 | | |
| | %Atômic | 64.67 | 35.29 | 0.01 | 0.02 | 0.02 | 100.00 | | |
| **Jenipapo 2** | Elements | C | O | S | Cl | K | Ca | Total | |
| | % p/p | 58.46 | 41.26 | 0.03 | 0.06 | 0.12 | 0.07 | 100.00 | |
| | %Atômic | 65.30 | 34.60 | 0.01 | 0.02 | 0.04 | 0.02 | 100.00 | |

It can be observed that the sulfur and potassium contents of the rosewood species are higher than that observed in Andiroba and Jenipapo species, while the content of Ca in Jenipapo and Andiroba species is almost the same for these species, but it is slightly higher for Rosewood species. On the other hand, the oxygen content in rosewood species is found to be lower than that in Andiroba and Jenipapo species. This could probably be due to rosewood being a much older tree compared to the two other species studied. Also, a small amount of sodium observed in one of the Rosewood samples suggests the possible presence of impurity.

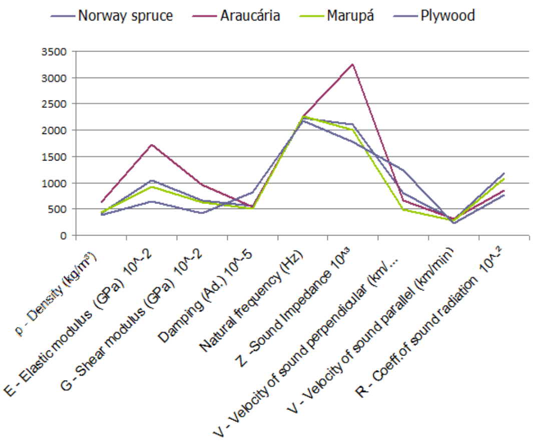
The properties of wood are influenced by the arrangement and quantity of the constituent components (cellulose, lignin, hemicelluloses) and by the structure of the wood [19].

Some properties of wood, such as fibre orientation and tubular structure, enable it to accumulate a greater volume of air in the fibres than in the cell walls. These characteristics have a significant impact on the speed of sound waves and the acoustic properties of each type of wood, and are an important feature for use in musical instruments [20].

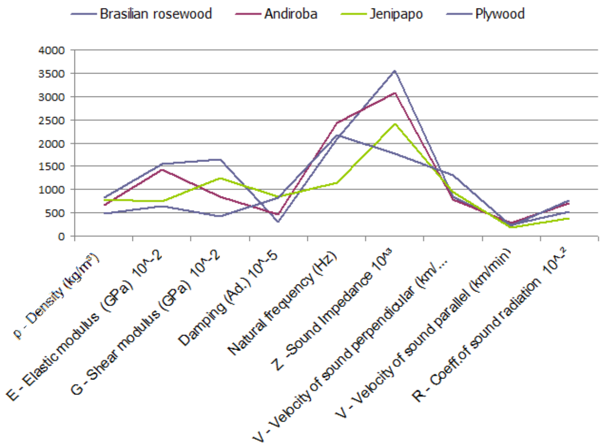
*3.2. Impulse excitation technique.*

The different properties of the wood used on both the soundboard and back side of the guitars are compared only numerically, and the bar graphs facilitated the visual identification of the wood with a behavior more similar to that of the standard. Accordingly, Figure 6 shows the results obtained from various tests carried out on wood used for the soundboard and back side of the guitars.

Figure 6 (a) shows the results of the velocity of sound on spruce, Marupá, Araucaria, and plywood of the soundboard of the acoustic box, while Figure 6 (b) shows similar results for rosewood, Andiroba, Jenipapo, and plywood. It may be noted that one should compare the results of Araucária, Marupá, and plywood with those of Norway spruce, which are the best and standard materials. It can be seen from these figures that Marupá exhibits characteristics that are more similar to those of Norway spruce than the other samples.




**(a)**




**(b)**

**Figure 6. (a)** Comparison of various properties of wood species for use in the harmonic soundboard; **(b)** Comparison of various properties of the back body of classical guitar with those of corresponding standard wood species.

Although the shear modulus is an engineering property studied, it is not a component that directly influences the timbre. The level of importance of the shear modulus for the guitar is very low.

Tables (5 and 6) show comparative results of various properties based on the above-mentioned Fig. 6 (a and b) of different wood species used in this study for the soundboard part and bottom of the loudspeaker obtained by impulse excitation technique. It may be noted that the method of absolute differences (Eqn. 5) was used to compare each property with the two traditional/standard woods (Norway spruce for the soundboard and rosewood for the bottom). If one were to substitute values of Norway spruce or rosewood, it would be seen that the property shown in Eqn. 5 would result in zero, while all other woods would have different results, but the best approximation to zero means the best wood for that property. It can be seen from the tables that Marupá samples show results closer to that of the spruce, while samples of Andiroba showed results closer to that of the Brazilian rosewood compared to the other species analyzed.

**Table 4.a.** The results of the analysis were made using the impulse excitation technique in the top wood.

| Name of test | The first best approximation with spruce | The second best approximation with spruce |
|---|---|---|
| ρ - Density | Marupá | Plywood |
| E - Elastic modulus | Marupá | Plywood |
| R - Coeff.of sound radiation | Marupá | Plywood |

| Name of test | The first best approximation with spruce | The second best approximation with spruce |
|---|---|---|
| G - Shear modulus | Marupá | Plywood |
| Damping (Ad.) | Araucária | Marupá |
| V - Velocity of sound parallel | Araucária | Marupá |
| Z -Sound Impedance | Marupá | Plywood |
| V. of sound perpendicular | Araucária | Marupá |

**Table 4.b.** The results of the analysis were made using the impulse excitation technique in the wood at the bottom of the loudspeaker.

| Name of tests | The first best approximation with rosewood | The second-best approximation with rosewood |
|---|---|---|
| ρ - Density | Andiroba | Jenipapo |
| E - Elastic modulus | Andiroba | Jenipapo |
| R - Coeff. of sound radiation | Jenipapo | Andiroba |
| G - Shear modulus | Jenipapo | Andiroba |
| Damping (Ad.) | Andiroba | Plywood |
| V - Velocity of sound parallel | Andiroba | Plywood |
| Z -Sound Impedance | Jenipapo | Andiroba |
| V. of sound perpendicular | Andiroba | Jenipapo |

The results of the properties obtained, as well as the studies already described in the literature [21], point to the fact that Marupá is a promising wood for a good quality construction of the soundboard. Marupá is a wood that grows fast to moderately and will hardly enter the endangered species list. Most of the characteristics of the spruce were found in Marupá. Still, it must be considered that the damping and velocity of sound in the Araucaria wood are also comparable to parameters that are close to that of the reference wood species. However, this difference is very small in relation to that of the Marupá.

Fast-growing alternative wood species with traditional wood characteristics are being explored by instrument makers and wood scientists, but wood workability and consumer choice would ultimately limit the range of replacement woods. Specific cultivation tends to increase biodiversity, which is declining every day with reduced pollinators and seed-dispersing mammals. A favorable inclination would be sustained agroecological cultivation with controlled removals and replenishments [22]. Likewise, the results of this study point to Andiroba as a promising wood for the construction of the bottom of the guitar body. Andiroba has seeds that are used in the cosmetics industry, which makes this species economically important and leads to a process of reforestation and forest management.

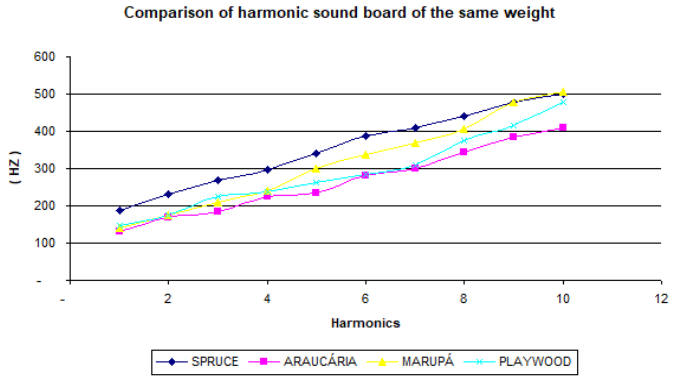
Further, as can be seen from Table 6, the impedance and sound radiation values of Jenipapo are not close to the reference values as were the values of Andiroba. The other characteristics of Andiroba wood are closer to those of rosewood. The shear modulus, despite being an important engineering constant, is not a parameter that can directly interfere with the timbre of the material.

The determination of other properties, viz., moduli of elasticity and shear, damping, sound impedance, and sound irradiation coefficient, was done only in sonelastic equipment. When confronting the importance of engineering properties related to acoustic properties in musical instruments, such as damping and impedance, one can notice a direct and indirect proportionality relationship with the density of the analyzed materials [22-24].

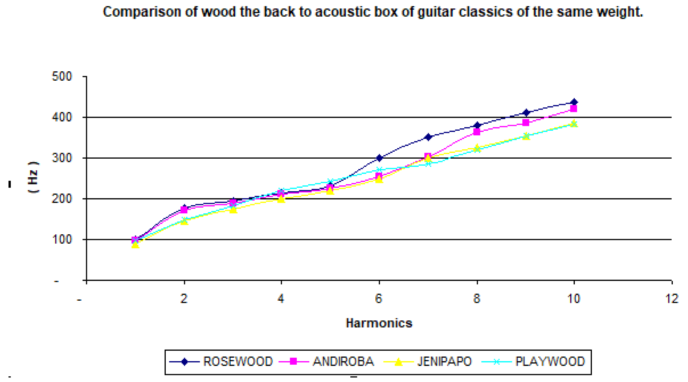
Different properties of the wood used on the soundboard of the guitar and body back (acoustic box) can be compared only numerically. A bar graph (not shown) would have facilitated the visual identification of the woods with behavior more similar to those of the standard woods (Spruce and Rosewood) used in these parts of the guitar.

*3.3 Signal analysis.*

Figure 7 (a) shows a comparison of the first harmonics of the same wood species of the same weight (approximately 120 g ± 2 g), all of these used in the top part of the soundboard and back body of a guitar. On the other hand, Figure 7 (b) shows the comparison of frequencies of the background of an acoustic box of guitar classics of the same weight (approximately 208 g ± 2 g) of Brazilian rosewood, Andiroba, Jenipapo, and plywood.




**(a)**




**(b)**

**Figure 7. (a)** Comparison of the harmonic soundboard of the same weight; **(b)** Comparison of wood the back to the acoustic box of guitar classics of the same weight.

It is reported that the difference in energy loss of the main frequency and partial frequencies is smaller over the decay time; this material will sound with a higher sound level. In addition, the regularity of the spectrum is also considered a quality characteristic for a good selection of materials. Since the efficiency of acoustic radiation is more dependent on frequency than on energy loss factors. [25]. The greater the complexity of the application of the material, the greater the requirement for characterizing this material with the reduction of variables in orthotropic material and irregular geometry. Furthermore, each sample and thickness has a specific behavior and must be applied consistently to produce better results without oversizing the chosen material [26]. It is noteworthy that in the case of this study, sound propagation occurs in the solid and not in the air, as it occurs under the influence of the guitar's wood.

Contemporary luthiers know more about Indian rosewood than Brazilian rosewood because there has been a decline in Brazilian species since the 1970s when other species were sought to supply the music market [24]. Currently, Indian rosewood is also endangered, and management practices and searches for substitute species are being studied for the trade of pieces and musical instruments.

Under certain boundary conditions, it leads to significant changes in vibration modes. For this reason, the vibration of the guitar body without a neck and with a neck differs from the loose plates. At low frequencies, the amplitudes of the vibrations of the back and side back and side plates are similar in size [27].

For the identity of a musical instrument, analyzing the harmonic series can be the main defining parameter of the timbre. The harmonic series can be called a group of frequencies in a series, and in this study, seven frequencies were analyzed, with the first frequency being the fundamental wave and the following ones being the first six overtones. The fifth overtone is considered an important acoustic constant.

It can be seen that Marupá and Andiroba are the woods that present properties that are more similar to spruce and rosewood, respectively. The analysis of signals carried out through the Fourier analysis using a frequency response function (FRF) showed that the closest combination of fundamental wave and secondary sound waves also coincides with density properties and rigidity or flexibility, taking into account the optimal reference appropriation of the rosewood and the spruce wood.

## 4. Conclusions

Considering the results obtained through the experiments and analysis carried out in this study and their comparison with standard wood species used for musical instruments in general and guitar in particular, the conclusions based on these can be summarized as follows: Four Brazilian wood species, viz., Marupá and Araucaria, for the top and Andiroba and Jenipapo species for the back of the guitar's sound box have been analyzed as possible alternate wood for the standard woods, viz., Norway spruce and rosewood to be used both in the soundboard and at the back body of a guitar. The tests carried out to compare the woods used for the soundboard and acoustic box of the guitar in the back of the guitar revealed that Marupá species is the closest wood to spruce Norway and Andiroba is the most similar wood to Jacarandá used for the back bottom of the guitar. However, all four wood species analyzed exhibited results closer to the reference wood species (Norway spruce and rosewood) than the plywood.

The results obtained, as well as the studies already described in the literature, indicate that the Marupá species represents a promising wood for the construction of the soundboard of guitars, replacing the Norway spruce used generally in these musical instruments. This should be considered most significant because this species shows rapid growth and will hardly enter the list of endangered species, thus making this species potentially preserved and part of a process of reforestation and forest management. Based on the results obtained, some Brazilian woods can be identified as exhibiting required characteristics that are closest to the behavior and properties of standard woods used in guitars. Considering the fact that the sonority of the guitar varies with the volume and architecture of the auditorium and the lining of the walls, ceiling, and floor, the criterion for the evaluation of the results obtained (the graphic method or the absolute differences in relation to the reference woods) seems to be adequate to identify the most similar woods to replace noble and traditional woods used in classical guitars, viz., Norway spruce (for top) and the Jacarandá (for bottom). In addition, this criterion makes it possible to evaluate other alternative woods that have not been studied and, therefore, can be evaluated for the said purpose. It is hoped that the methodology developed for this study could be applied to other alternative woods so that it would be possible to identify other woods similar to Norway spruce.

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## Conflicts of Interest

The authors declare there are no financial and personal relationships with other people or organizations through the following: employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding, which would inappropriately influence this study.

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