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Ultrasound characterization of guitar woods

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Abstract This paper reports the ultrasound characterization of nine species of woods used on the fabrication of guitars. This method uses short ultrasonic square pulses (12 mSec) to measure the elastic constants of the woods. Also taking advantage of the spectral content of the short pulses, it was possible to measure the frequency response of the samples. This frequency response allows us by Fourier spectral analysis to assign a characteristic musical note to each wood. Our results show that each specie can amplify only a specific group of musical notes.

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1 Introduction

The guitar is perhaps one of the most played musical instruments around the world. The guitar consists of a body with a rigid neck to which the strings are attached. Generally, the guitar is constructed with different woods. The material from which the guitar is made, significantly influences the quality, color and, tone of the produced sound. The top and back are the most important components of the guitar, both, acoustically and structurally. Since its origin, the selection of guitar wood is based on luthiers (stringed instrument maker) wisdom, who several centuries ago identified some kinds of woods as the ideal

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woods. This situation holds true today, due to the mechanical properties of these woods, particularly the properties that characterize the behavior of the top and back in flexural vibration. The three fundamentals mechanical properties of the guitar woods that characterize its acoustical and structural qualities are (1) density, (2) Young's modulus and, (3) damping of waves traveling along the grain.

The luthier choice of wood for guitar is based on the external aspect, for example, the absence of defects like; resin pockets, knots, compression or tension wood. However, there is not a scientific knowledge on this selection. Several methods have been reported to characterize woods, depending on the type of energy used, it is possible to measure different physical properties of the wood, for example, Zoughi, who measured the ionic concentration and moisture content employing electromagnetic waves (Zoughi, 1990), Chan *et. al.* investigated the modification of the acoustic velocity by the moisture content and temperature (Chan et al, 2010), Nicolotti *et. al.* employed three different tomographic techniques to characterize the internal defects in woods (Nicolotti et al, 2003), in similar way Baradit *et. al.* report the use of microwave technique to detect knots on woods (Baradit et al, 2006), Sanabria *et. al.* use Air-coupled ultrasound to detect structural defects on glue timber products (Sanabria et al, 2010), Bocur who measured the density employing X-ray (Bucur, 1985). However, those methods provide only structural information, but not allow the characterization of acoustical properties of wood. Another method has been employed to reproduce the ability of luthiers to select the adequate wood, this method uses an image analysis of the growth rings distance, and then correlates this analysis with the acoustical properties of the wood (density and Young's modulus) (Bella et al, 2002).

The acoustical parameter for characterization of wood for violins was described by the first time by Schelleng (Schelleng, 1982), who employed a resonance frequency method. The advance on theoretical understanding of the propagation of linear vibration in solids has permitted the development of high precision methods of characterization and measurement of elastic constants as well as the corresponding damping constants of the woods. These methods have been applied by several authors to find the adequate wood, for example, Schelling used the density (ρ) and the acoustic impedance (ρ x V)to find the acoustic radiation (V/ρ). This last parameter can help in matching two violin plates with different stiffnesses and densities but which the acoustic radiation is identical (Schelleng, 1982). Bocur used an ultrasound velocity with an excitation frequency of 1 MHz to measure 12 elastic constants (3 Young's moduli, 3 shear moduli, and 6 Poisson's ratios) (Bucur, 1987). Sedik et al. measured the acoustic properties of tropical woods, employing a non contact flexural vibration system (Sedik et al, 2010). Here, a bulk of wood is exposed to vibration in a range of 1 Hz to 1000 Hz, to find the resonance frequency.

The goal of this paper is to characterize nine different woods (spruce, red cedar (Canada), red cedar (Honduras), palo santo (Brazil), palo santo (Indian), ebony, purple-heart, mahogany, and, spring tree) used on the fabrication of classic guitar. Ultrasound technique was employed to measure the elastics constants for the different species of wood used in this work, our results are in agreement with those reported in the literature using similar methods. However, our method takes advantage of spectral characteristics of ultrasonic short pulses (12 mSec) to measure the frequency response of the sample. This measurement allows by mean of the Fourier spectral analysis to assign a characteristic musical note to each sample. This is an important result because allows to select the adequate wood, according to the quality, color and, tone of the produced sound.

2 Guitar wood structure

Generally, wood is considered as anisotropic material, the anisotropy come from its internal structure. This structure contains natural fibers arranged in annual rings. To understand the wood structure since ultrasound point of view, it is necessary to consider three different directions with different elastic properties; longitudinal (L), radial (R) and, tangential (T).

The L axis is parallel to fibers; along this axis the fibers are partially distributed by "horizontal tubes". On the R direction, longitudinal cells, tracheids, and fibers tend to be aligned, however along the T direction are randomly distributed. The complex structure of the wood exhibits orthotroptic properties that affect the way that, a sound wave propagates through it. For example in the L direction, the arrangement of the wood fibers provides high values of acoustical constants.

The elastic behavior of the wood can be modeled in the same way of all anisotropic solids, by mean of Hooke's law:

$$[\sigma_{ij}] = [C_{ijkl}][\epsilon_{kl}] \tag{1}$$

This law relates the volume average of stress $[\sigma_{ij}]$ to the volume average of strains $[\epsilon_{kl}]$ by the elastic constants $[C_{ijkl}]$. After a simple algebraic manipulation and considering the orthotroptic materials properties, the stiffness matrix can be written as follow:

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{21} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{31} & c_{32} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \tag{2}$$

The stiffness matrix (Eq.2)contains nine independent constants: six diagonal terms (C_{11}, C_{22}, C_{33}, C_{44}, C_{55}, C_{66}) and three off-diagonal terms (C_{12}, C_{13}, C_{23}). We can see the complex elastic symmetry, the constants are influenced by three mutually perpendicular planes of elastic symmetry, (LR, RT and, LT planes).

Because its orthotroptic nature, the wood exhibits a variation on the physical response to the applied stress along different axes. For example, when an ultrasound wave is injected into wood, it couples to each fiber in several modes (longitudinal, flexural, and torsional). The physical properties of the cellular wall such as the density, the rigidity modulus, etc. and the shape and size of the fibers or of other elements affect the transmitted ultrasound field. The ultrasound wave propagation trough wood can be modeled by Christoffel's equations. This equations supply the relations between the elastic constants C_{ijkl} and the phase velocity $v_{phase} = V$ of ultrasonic waves propagating in the medium. For example, if we propagate a wave with the form

$$u_i = A_i \exp(i(k_j x_j - wt)) \tag{3}$$

In the plane RL(n_1,n_2), and $n_3 = 0$, we can calculate the phase velocities with the following formula(Christoffel's equation)

$$\begin{pmatrix} c_{11}n_1^2 + c_{66}n_2^2 - \rho V^2 & (c_{12}+c_{66})n_1 n_2 & 0 \\ (c_{12}+c_{66})n_1 n_2 & c_{66}n_1^2 + c_{22}n_2^2 - \rho V^2 & 0 \\ 0 & 0 & c_{55}n_1^2 + c_{44}n_2^2 - \rho V^2 \end{pmatrix} \tag{4}$$

Expanding the determinant:

$$\begin{aligned} \{c_{55}n_1^2 + c_{44}n_2^2 - \rho V^2\}\{(c_{66}n_1^2 + c_{22}n_2^2 - \rho V^2)(c_{11}n_1^2 + c_{66}n_2^2 - \rho V^2) \\ -(c_{12}+c_{66})^2 n_1^2 n_2^2\} = 0 \end{aligned} \tag{5}$$

By setting either the first or the second factor to zero, is possible to calculate the phase velocity of the wave for each mode of propagation.

3 Experimental

The table 1 summarizes the sizes and densities for nine species of wood used in this work. These species were selected because are the most employed on the construction of guitars. Each sample was under drying process along 10 years into a controlled environment of temperature (25 to 27 ^{o}C) and humidity. Before being tested each sample was put under a drying process of 14 hours at 280 ^{o}C, after that process the average moisture of the samples was 5%.

Table 1 Size and densities for the different species employed to construct guitars.

Species	LxWxH (mm)	ρ(Kg/m^3)
red cedar(Canada)	85.25 x 43.20 x 3.82	332.66
spruce	85.66 x 42.09 x 5.00	450.27
mahogany	86.04 x 43.38 x 4.71	525.18
red cedar(Honduras)	85.71 x 43.11 x 7.34	541.81
spring tree	88.12 x 42.70 x 4.62	629.73
palo santo(Indian)	84.71 x 42.58 x 4.48	651.88
palo santo(Brazil)	84.81 x 42.43 x 3.09	914.40
purple-heart	41.13 x 17.25 x 7.18	916.52
ebony	73.80 x 45.78 x 6.70	1115.87

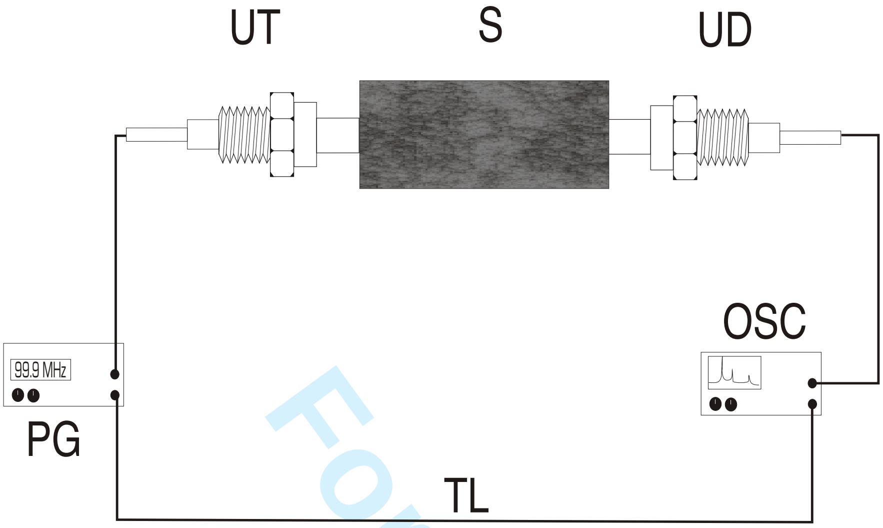

Fig. 1 Ultrasound setup. UT, ultrasound transducer, S sample, UD ultrasound detector, PG width modulable pulse generator, TL trigger, OSC oscilloscope

The figure 1 shows the experimental setup for ultrasound characterization of guitar wood samples.

To observe and capture the data an oscilloscope model DPO7054 from Tektronix of 500 MHz of bandwidth,was used. The pulses were generated by a 16F84A microcontroller from Microchip, operating at 4 Mhz. This microcontroller was programed to modulate the width of the ultrasonic pulses.

To generate the ultrasonic signal an ultrasound transducer model XX.XX was used. The ultrasonic signal was detected by an ultrasound detector, figure 2 shows an example of the signal detected. after acquisition, each signal was post-processing following the next procedure; first, the noise was removed by calculating the median over 100 adjacent points. After, the derivate of the signal was calculated, and finally is obtained the rate of change of the voltage with respect to the time, this last measurement allows us to establish the fly time of the ultrasonic pulse. The table 2 shows a comparison between the velocities measured with our system and the results reported in (Bucur, 2006; Blas, 1996). From this comparison we selected the parameter corresponding to 10% of the derivate.

Taking advantage of the spectral content of short pulse, it was possible to measure the acoustical response of the samples. A 12 mSec pulses were

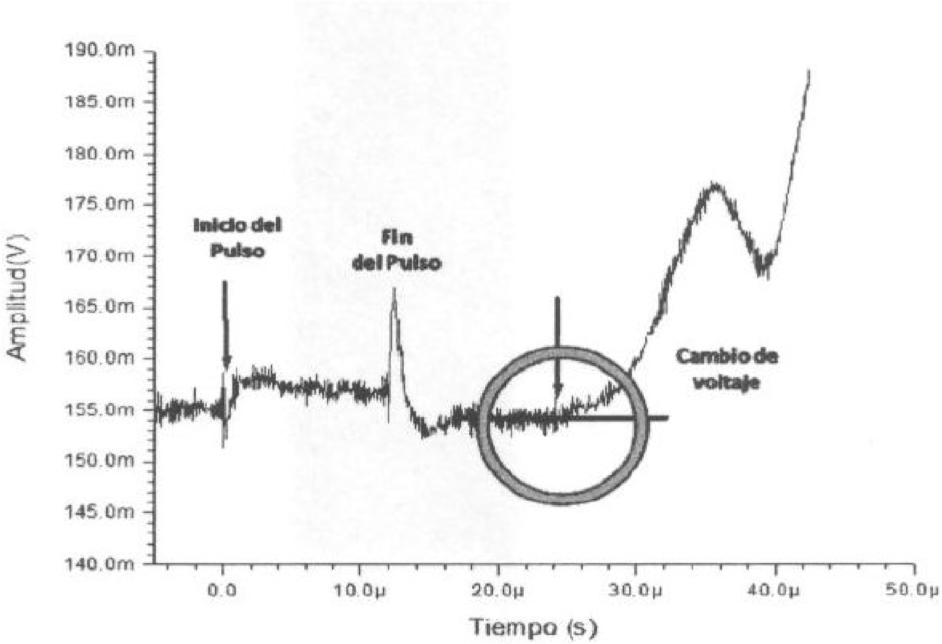

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Table 2 Velocities comparison between the velocities measured with our system and the results reported in (Bucur, 2006; Blas, 1996)

Derivate(%)	spruce	(Bucur, 2006)	error %	red cedar	(Blas, 1996)	error %
10	1769	1793	1.33	1610	1600	-0.84
15	1697	”	3.6	1588	”	0.92
20	1648	”	6.4	1588	”	2.9
25	1600	”	9.6	1542	”	4.3
30	1576	”	10.6	1531	”	4.3

propagated through each sample. The acoustic signal of each sample was analyzed using the Fast Fourier Transform algorithm. To each peak of the Fourier spectra was assigned their corresponding musical note. The figure 3 shows Fourier spectra calculated for purple-heart sample, here the peak corresponding to musical note Sol_6 has the maximum amplitude, also the adjacent peaks correspond to Si_5 and Re_7 have similar amplitude, this is important, because the combination of those musical notes, forms the guitar chord G major (Sol major). This imply that the purple-heart, can produce with great quality the sound corresponding to this chord. Following this context, is possible to assign to each sample, their corresponding musical note by analyzing their Fourier spectra.

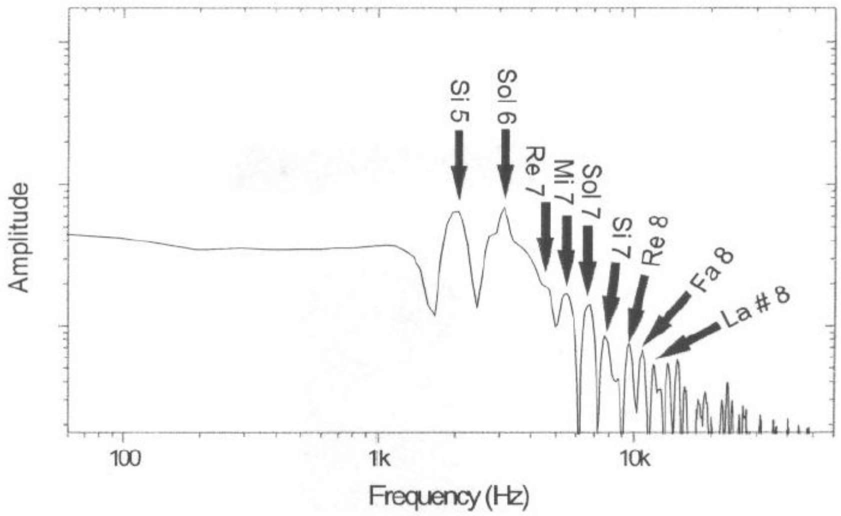

Fig. 3 Fourier spectra calculated for purple-heart sample

4 Results and discussion

The table 3 shows the velocities measured for each wood species, it is important to notice the difference of velocities between L axis and the R and T axes. This behavior is similar for all species studied. The anisotropy values exhibited by low density woods (red cedar and spruce) as compared with the anisotropy values of high density woods (Palo santo and ebony), show a great similarity, this suggest that not only the ρ (density) parameter determines the propagation velocity of the sound, also particular properties of each species, for example the quantity of fibers/ m^2, the thickness and the large of them, play an important role on the sound propagation.

Table 3 Measured values of velocities for L, R, and T axes

Species	$V_{11}[\frac{m}{s}]$	$V_{22}[\frac{m}{s}]$	$V_{33}[\frac{m}{s}]$	$\beta = \frac{V_{11}}{V_{22}}$	$\gamma = \frac{V_{11}}{V_{33}}$
red cedar(Canada)	4262.5	1610.68	873.05	2.54	4.8
spruce	4508.77	1769.03	1190.31	2.54	3.78
mahogany	3955.86	1535.57	1772.15	257	2.23
red cedar(Honduras)	3895.86	1227.33	1048.57	3.05	3.07
spring tree	3369.23	1986.04	1169.62	1.6	2.8
palo santo(Indian)	3894.71	1622.09	1756.26	2.40	2.22
palo santo(Brazil)	3727.91	1749.69	1211.76	2.13	3.07
purple-heart	4115.02	1337.20	1561.54	3.07	2.06
ebony	4211.10	2817.23	1558.12	1.49	2.7

The moisture is a determinant factor in the ultrasound propagation (James et al, 1982; Mishiro, 1995; Chan et al, 2010),thus is, the measured values in our samples are lower than the values reported in (Bucur, 2006) for similar species, this is because our samples have a 5 % of moisture as compared with 12% of the samples used in (Bucur, 2006). The table 4 show the calculated values

Table 4 Elastic constants corresponding to each studied species

Species	$C_{11}10^8[\frac{N}{m^2}]$	$C_{22}10^8[\frac{N}{m^2}]$	$C_{33}10^8[\frac{N}{m^2}]$
red cedar(Canada)	60.44	8.63	2.53
spruce	91.53	14.09	6.37
mahogany	82.18	12.38	16.49
red cedar(Honduras)	82.23	8.84	5.95
spring tree	71.48	24.83	8.61
palo santo(Indian)	98.88	17.15	20.10
palo santo(Brazil)	127.07	27.99	13.42
purple-heart	155.19	16.38	22.34
ebony	197.87	88.55	27.04

for C_{11}, C_{33}, and C_{33}. An strong difference is observed between the values measured for C_{11}, C_{33}, and C_{33}, resulting from the corresponding values of V_{11}, V_{22} and, V_{33}. This indicate a a major resistance to deformations on the L direction as compared with the other directions. For example the low value exhibited by the red cedar (Canada) and spruce, on the T axis, can explain the low resistant for the impact presented by the guitars constructed from this species.

Table 5 Musical notes assigned to each axes.

Species	L	T	R
red cedar(Canada)	Fa_6	Do_4	Re_4
spruce	La_6	Fa_5	Sol_4
mahogany	$\mathrm{Re}_{6\#}$	Sol_5	Sol_4
red cedar(Honduras)	Sol_6	Si_4	Re_3
spring tree	$\mathrm{Fa}_{6\#}$	$\mathrm{Sol}_{5\#}$	$\mathrm{Re}_{5\#}$
palo santo(Indian)	Sol_6	Mi_5	Si_5
palo santo(Brazil)	La_6	Sol_5	$\mathrm{Fa}_{4\#}$
purple-heart	Sol_6	Fa_5	$\mathrm{Re}_{4\#}$
ebony	$\mathrm{La}_{6\#}$	$\mathrm{Sol}_{5\#}$	$\mathrm{Re}_{5\#}$

The table 5 shows musical notes assigned by mean of the frequency analysis. This analysis allow to find the range of frequencies that are compatibles with each species. This is an important result, because is possible through this analysis to evaluate the natural tuning of each species. For example, the purple-heart, has assigned the musical note Sol_6 over the L axis, this imply that this species allows the amplification of the frequencies corresponding to this musical note. Also, as is depicted in figure 3, there are other frequencies , this frequencies are relate with other musical notes (Si_5 and Re_7) that complement the musical chord Sol major.

5 Conclusion

The frequency response of the woods used to construct classic guitars can be characterized using ultrasonic short pulsed. This characterization allows to evaluate the specific range of frequencies that are compatible with each specie of wood used in the guitar construction. Also the elastic constants can be evaluated. Each studied specie has a very specific frequency response and elastic constants values, the knowledge of these parameters allows the adequate selection of the wood.

References

Baradit E, Aedo R, Correa J (2006) Knots detection in wood using microwaves. Wood Science and Technology 40:118–123

Bella AD, Piasentini F, Zecchin R (2002) Violin top wood qualification: influence of growth ring width on acoustical properties of red spruce. Catgut Acoust Soc J 4(6, 2):2225

Blas L (1996) Caracteristicas anatomicas y acusticas de algunas clases de angioespermas. Master's thesis, UNAM

Bucur V (1985) Ultrasonics, hardness and x-ray densitometric analysis of wood. Ultrsonics 23(6):269–275

Bucur V (1987) Varieties of resonance wood and their elastic constants. Catgut Acoust Soc J 47:42–48

Bucur V (2006) Acoustic of Wood, 2nd edn. Springer Verlag

Chan M, Walker J, Carolyn JR (2010) Effects of moisture content and temperature on acoustic velocity and dynamic moe of radiata pine sapwood boards. Wood Science and Technology pp 1–18

James WL, Boone RS, l Galligan W (1982) Using speed of sound in wood to monitor drying in a kiln. Forest Prod J 32(9):27–34

Mishiro A (1995) Ultrasonic velocity in wood and its moisture content, part i. effects of moisture gradients on ultrasonic velocity in wood. Mokuzai Gakkaishi 41:1086–1092

Nicolotti G, Socco L, Martinis R, Godio A, Sambuelli L (2003) Application and comparison of three tomographic techniques for detection of decay in trees. Journal of Arboliculture 29(2):66–78

Sanabria S, Mueller C, Neuenschwander J, Niemz P, Sennhauser U (2010) Air-coupled ultrasound as an accurate and reproducible method for bonding assessment of glued timber. Wood Science and Technology pp 1–15

Schelleng J (1982) Wood for violins. Catgut Acoust Soc Newsl 37:819

Sedik Y, Hamdan S, Jusoh I, Hasan M (2010) Acoustic properties of selected tropical wood species. J Nondestruct Eval 29:38–42

Zoughi R (1990) Microwave nondestructive testing: Theories and applications. Int Adv Nondestruct Test 15:225–288