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Full Length Research Paper

Vibration analysis in the design and construction of an acoustic guitar

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One of the main problems encountered in developing and building an acoustic guitar is to establish a formal methodology that allows us to observe the impact of some parameters involved in the process. This paper propose a modal analysis in the different stages of construction, and it is performed by -a finite element analysis of the soundboard of the instrument according to the relationship that that have the- frequencies and vibration modes, here, a set of certain parameters in the design are used to improve sound performance.

Key words: Vibration analysis, modal analysis, acoustic guitar.

INTRODUCTION

The guitar is considered among the plucked string instruments. The instrument of 6-strings is known including different variants that have been developed. Among them are the 7-string guitar instrument used in Russia and the 10-string guitar which is one of the last designed. The basic features of the modern guitar were proposed by the “Luthier” of Antonio Torres (1817 to 1892). Another contribution was the design of the internal structure that accompanies the soundboard (Thomas and Graham, 2010; Espinós, 1977).

Antonio Torres carried out some experiments both in shape and proportions, the one he considered to be important was the soundboard, and in fact, his interest in the guitar cover (top) was so large that motivated him to design a guitar with paper-mache, where the back and ribs were made of cardboard, showing the predominant importance of the soundboard in the production of tone. As this instrument is not able to be used, it is impossible to determine whether the experiment supported the idea of the relationship between the top and bottom as well as sides. In general, their soundboards are thicker in the central area around the bridge and above the mouth (2.5 mm), decreasing in thickness at the edges, about 1.4 mm only. The paper-mache guitar has a thickness of only 0.4 mm at the edges of the cover (Romanillo, 1997). For the development of this paper, we consider the soundboard as an important part in the construction and sound quality of the instrument, in this way we propose to carry out some soundboards analysis using the original features that the guitar maker Antonio Torres proposed, but we considered a five bar structure with some particular proportions which will be described later.

Signal processing techniques in acoustics includes some topics which can be variables such as wave propagation, amplitude considerations, spectral content of wavelength and phase. The phase is mainly of interest when the waves interact with each other, as well as, the environment and the imposition of boundary conditions that leads to the normal mode vibrations. All these conditions are present in all musical instruments including the guitar, which will be considered in the present work. In this way the signal processing becomes one of the essential techniques for understanding and modeling the structure of musical instruments as well as the quality of the sound. Some theoretical and experimental techniques for studying and modeling the instrument behavior are the modal analysis of vibrations, particularly in the case of violins and guitars , some patterns are set up.

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Many of the previously described techniques for violins and guitars were already established in some previous studies. Another technique used to assess the performance of the instrument when performing a frequency analysis is the Fourier transform, and fast Fourier transform (FFT). The FFT allows observation of the spectrum of the signal and in turn allows you to find the associated and registered excitations as transfer functions. Along with these techniques, it is important to consider the structural analysis known as finite element, and in this paper a finite element analysis is presented, where the vibration modes of the guitar soundboards taking into account the proportions that Antonio Torres proposed in his work.

Musical instruments are complex structures, which does not have a direct relationship between the features and materials with the sounds produced by the instrument. To classify the musical aspects of sounds for certain musical instruments proposed by Rolf and Uwe (2008), its characteristics can be grouped into four major features, listed as:

1. Ring (sound quality)
2. Attack behavior
3. Overall loudness
4. Degree of possible ring variation.

Instrument builders and musicians are convinced that, it is primarily these features which determine instrument quality and character. The importance of timbre is evident mostly within a given instrument family, rather than in comparison between families. A concrete example is the classical guitar, where the timbre difference between the guitars built by cedar and spruce is quite small, but it is clearly perceived by the experts (Pérez et al., 2002). It is this difference that determines what type of instrument is to play for a specific musical style. The difference in both instruments is the type of wood used on the top cover, as some performers also require some kind of skill to play an instrument to another. Some others say that the guitars built with spruce require time to mature before reaching their ultimate sound quality.

GUITAR STRUCTURE

The development of a guitar from design to construction is an art (Rubén et al. 2009), and now it is very common to follow the development and which is recognized by creative designs. One method is to seek and adapt various methods of construction from other authors to improve the quality of sound, but this method does not always yield the best results.

The guitar as an instruments composed two components in the sounding board, part of the soundboard which resembles a membrane that will grab and make the tie string vibrations instead of the bridge,

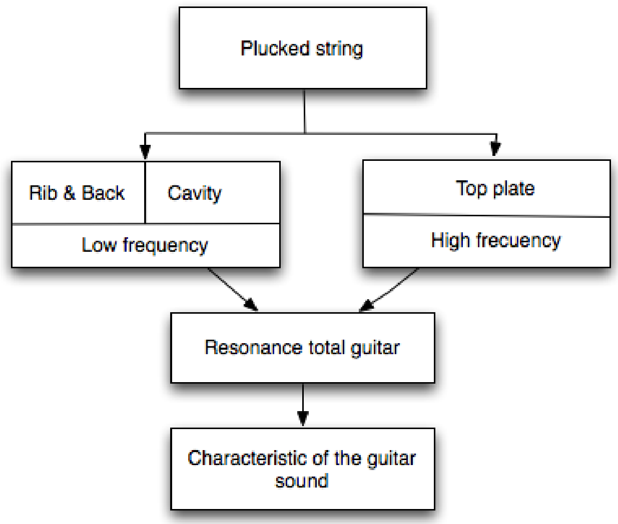


Figure 1. Guitar sound scheme works.

the second part is the background, that is to say that, it functions as the support and border conditions of the soundboard.

The production of acoustic guitar sound is the vibration system of a membrane which is represented by the soundboard and the back and ribs in Figure 1, that shows the sound generation system on the guitar taking into account the elements. Basically, it has two parts and the contribution in the generation of the frequency spectrum; this way you can see how the sound generated from the string is pressed until the environment is projected.

This analysis is focused only on the soundboard of the guitar, taking into account several factors; the first assumption was made by Antonio Torres, and the second was the consideration of the soundboard as a structural part of the instrument, where the vibration was made through a bridge of a part of the vibrating membrane and a part of the cavity structure which also makes a vibration and air displacement.

Figure 2 presents the plans of one of the guitars built by Antonio Torres with a 5 bar type and 7 bar type structures. Development of the analysis was performed on the guitar which uses some features similar to those used by Torres in Figure 2, which shows the development of one of the soundboards by some experiments that were performed.

THE SOUNDBOARD SYSTEM

Generally, the top cover of the guitar is made of cedar or spruce wood with a length of approximately 500 mm and the thickness varies from 3 to 1.5 mm which is not uniform with that of the manufacturers of the caps who

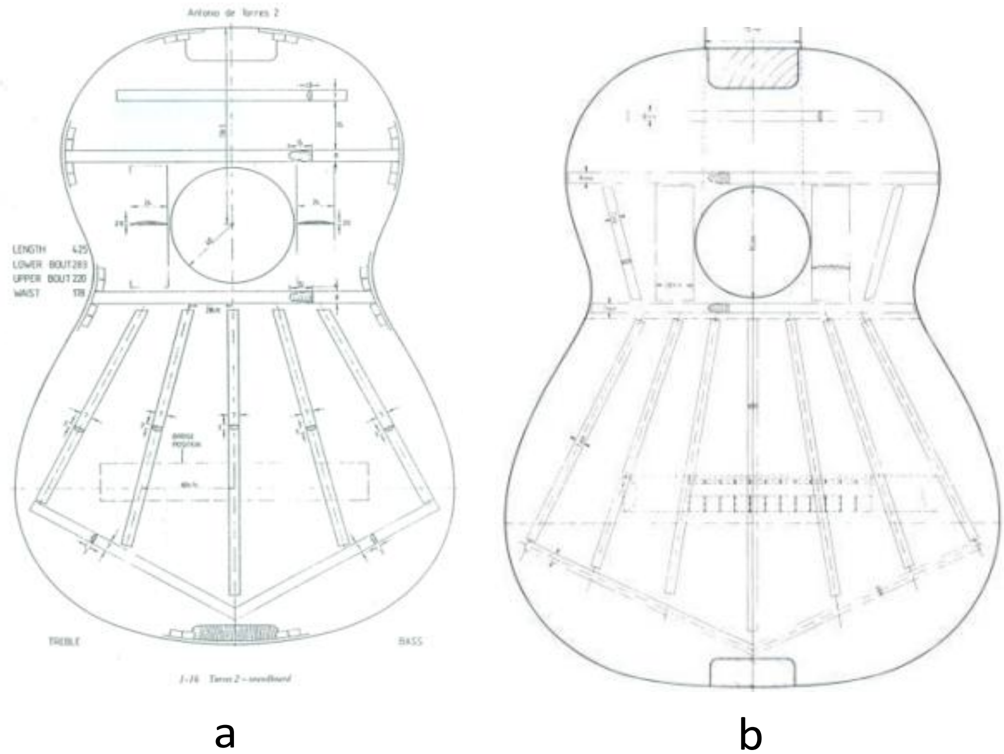


Figure 2. Plans guitar. a) 5 bar, b) 7 bar.

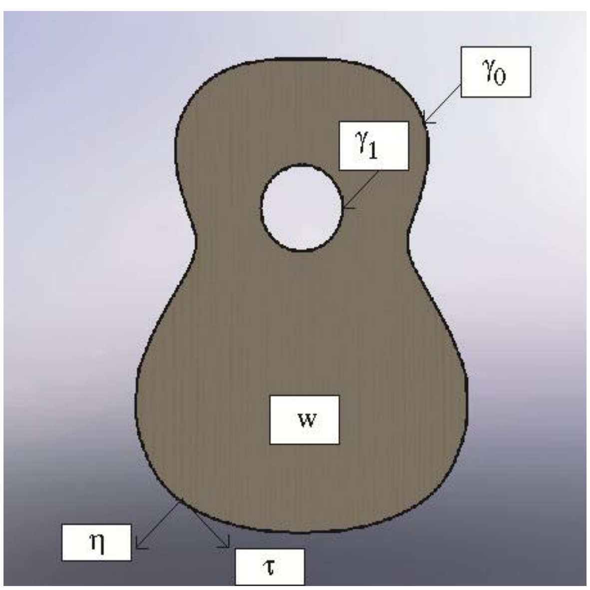


Figure 3. Description of the soundboard top.

used a thickness of 2.5 mm in the thickest part and 1. 7 mm in the thinnest part; this variation in the case of the thinnest part of the cover is around a bridge.

The plate of the soundboard top is considered as W in R2, the boundary conditions can be decomposed into two parts; first, with the ribs $\gamma 0$ and the limit of the sound hole $\gamma 1$. The normal components to W in the outside top are considered as η =(ηx, ηy), as we can see in Figure 3. Also, the tangential components are orthonormal and considered as τ=(τx,τy).

The vibrations of the soundboard are written in general as a field of displacement μ_p (x, y).

$$\mu_p = (\mu_x(x,y), \mu_y(x,y), \mu_z(x,y),) \qquad (1)$$

The displacement presented in equation consists of vibration of the membrane that forms the top and on the other harmonic vibration known as flexion.

It is considered a model of the soundboard of the guitar modeled bending equation proposed by Kirchhoff-Love for an inhomogeneous material.

The vibration is described by a vertical movement which can be modeled by Equation 2.

$$\delta\rho_p \frac{\partial^2 u_p}{\partial t^2} + div \ \underline{\text{Div}\underline{M}} = fp \ \text{In W}$$

$$\underline{M}\text{-} \delta^3 C_{\underline{e}} (\nabla u_p) = 0 \ \text{In W In } \gamma 0$$

$$u_p = 0 \quad \partial_n u_p = 0 \qquad (2)$$

$(\underline{\underline{M}}n).\underline{n} = 0$ In $\gamma 1$

$(Div\underline{\underline{M}}).\underline{n} + \partial_\tau [(\underline{\underline{M}}n).\underline{\tau}] = 0$ In $\gamma 1$

Where M is the bending moment, $Div\underline{\underline{M}}$ effort both are considering the boundary conditions. Boundary conditions are physically two conditions considered as a top limit where it is assembled with the ribs $\gamma 0$ and is considered the limit of the sound hole $\gamma 1$.

Here, ρ is the density of the top wood that was manufactured. Also, C is the tensor hard this is used in the Kirchhoff-Love plate, in this case using the corresponding symmetrical components of three vectors Mxx, Myy and Mxy, this could be rewritten as shown in Equation 3 (Grégoire, 2002).

$$C\,\underline{\underline{M}} = \frac{1}{2}\begin{bmatrix} \frac{Ex}{1-VxyVyx} & -\frac{ExVxy}{1-VxyVyx} & 0 \\ -\frac{ExVyx}{1-VxyVyx} & \frac{Ex}{1-VxyVyx} & 0 \\ 0 & 0 & 2Gxy \end{bmatrix}\begin{bmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} \quad (3)$$

Where,

Ex and Ey: Young's modulus
Vxy and Vyx: Poisson ratios
Gxy: Shear modulus
δ : Thickness of the table
fp: Density of surface load
∂_n and ∂_τ: Tangential and normal derivatives
div: Vector divergence of order 2, considered as a scalar
∇: Gradient applied to a regular function of two variables, this result in a two-dimensional vector. $\nabla^{\mu_p}(x,y)=(\partial_x{}^{\mu_p}, \partial_y{}^{\mu_p})$
$\underline{e}$: Linear tensor operator, this result in a symmetrical tensor of order 2
Div: We consider the divergence Div as applied to tensors of order 2. Div M is a vector of two dimensions where the components are given by the divergence of each voltage vector related as

$$Div\begin{pmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \end{pmatrix} = \begin{pmatrix} \partial_x M_{xx} + \partial_y M_{xy} \\ \partial_x M_{yx} + \partial_y M_{yy} \end{pmatrix}$$

In practice, the equation takes into account the different losses that are made in the soundboard, so that is considered a real model. It is important to remember that different dissipation loss that occurs play an important role in the perception and sound quality in the production and manufacture of musical instruments.

It is therefore enough to propose a model to account for these different phenomena. In the same manner, it is also important to consider the effect of the string as the input source is used as the resounding theme for the vibrating plate. On the other hand, one can also analyze the loss characteristics of the sound box: losses at the edges due to the absorption of some of the elements used in assembling of the ribs, and the other example would be the components that make up the bridge, which is subjected to the soundboard. Radiation losses are taken into account automatically, due to the coupling between the plate and air. Other losses are caused by the coupling of the string and other internal losses are assumed to be due solely to the characteristics of visco-elastic as well as the loss of thermal origin.

A viscous damping term is used to simulate the phenomena of the delay in the law of the material behavior and allows dependency rate depreciation with respect to the material presented in Equation 5. In the equation, to simplify the repayment viscous coefficient, n is considered constant throughout the plate. Equation 6 is used to consider the reduction of the buffer to the terms of the air compression inside the box. Where, Rp is considered as the damping ratio.

$$\underline{\underline{M}} = \delta^3\, C\underline{\underline{\varepsilon}}\,(\nabla u_p) + n\frac{\partial}{\partial\tau}\delta^3\, C\underline{\underline{\varepsilon}}(\underline{\nabla}\, u_p),\ (n > 0) \quad (5)$$

$$\delta\rho_p R_p \frac{\partial up}{\partial\tau},\ (R_p > 0), \quad (6)$$

Considering Equation 5 and 6 which are the two terms of repayment, it is possible to rewrite the equation of the vibration plate in Kirchhoff-Love Equation 7.

$$\delta\rho_p \frac{\partial^2 u_p}{\partial t^2} + div\ \underline{Div\underline{\underline{M}}} + \delta\rho_p R_p \frac{\partial u_p}{\partial\tau} = fp, \quad \text{In W}$$

$$\underline{\underline{M}} - \delta^3\, C\underline{\underline{\varepsilon}}\,(\nabla u_p) - n\frac{\partial}{\partial\tau}\delta^3\, C\underline{\underline{\varepsilon}}(u_p) = 0 \quad \text{In W}$$

$$u_p = 0 \quad \partial_n u_p = 0 \ \text{In}\ \gamma 0 \quad (7)$$

$$(\underline{\underline{M}}\ n).\underline{n} = 0 \quad \text{In}\ \gamma 1$$

$$(Div\ \underline{\underline{M}}).\underline{n} + \partial_\tau [(\underline{\underline{M}}\ n).\underline{\tau}] = 0 \quad \text{In}\ \gamma 1$$

Then, the general solution to the top general equation is shown in Equation 8 as follow:

$$\delta\rho_p \frac{\partial^2 u_p}{\partial t^2} + (1 + n\frac{\partial}{\partial\tau})\ div\ \underline{Div\underline{\underline{M}}}\ \delta^3\, C\underline{\underline{\varepsilon}}\,(u_p) + \delta\rho_p R_p \frac{\partial u_p}{\partial\tau} = fp, \quad (8)$$

Moreover, the Equation 9 defines the K operator obtained from the Kirchhoff-Love plate:

$$K: u_p \rightarrow div_{\underline{Div}\underline{\underline{M}}} \delta^3 \, C^{\underline{\underline{\varepsilon}}} (u_p) \qquad (9)$$

In order to describe the behavior of the plate's membrane, the Equation 10 is considered, together with its solution presented in Equation 11 (Gregoire, 2002).

$$\delta\rho_p \frac{\partial^2 u_p}{\partial t^2} + \left(1 + n\frac{\partial}{\partial \tau}\right) k u_p + \delta\rho_p R_p \frac{\partial u_p}{\partial \tau} = f \text{ In } W$$

$$+ \text{ initial conditions} \qquad (10)$$

$$u_{p(x,y,t)} = \sum_{n=1}^{\infty} (A_n cos(w_n t) + B_n sin(w_n t) \, \Xi_n (x,y). \qquad (11)$$

For good sound quality in the guitar and the violin, it is essential to consider the vibration behavior of structural elements as mentioned previously and especially in the top cover (Thomas, 2001; Massmann, 1993). The luthiers generate taps on the top to feel the vibration characteristics of an instrument, taking extreme care in the fulcrum and the area generated by the shock. These characteristics are obtained by their experience and are all under a scheme agreed with these heuristic tests, where the builder is giving different thicknesses to the top until the desired sound is obtained, and on the other hand, others feel and they use the flexibility of the cap to take the decision of the finished thickness. For the final sound quality of the guitar, the frequency relationship between the top and bottom holding should be considered as shown in Figure 1.

MODAL ANALYSIS

One of the proposals in this paper is to analyze the characteristics of the top cover of the guitar in different stages of construction taking into account the previous discussion on the topic, and that, the vibrations present in the guitar in general can be described in terms of vibration modes produced by structural elements.

Normal modes of vibration are independent ways in which a structure attached an external stimulus. They are characterized by nodes and anti-nodes as well as the modal frequency and damping. The modal analysis test is an established method for the identification of modal parameters of a structure, such as natural frequencies, mode shapes and modal damping. This method has been defined and applied in the construction of violins and used by many builders to determine certain sonic characteristics of your instrument. The guitar has been extended and this test has been reported in some studies (Curtu et al., 2008; Bader, 2005). To obtain these modes, it is necessary to bring external stimulus structure in this case, would be represented by the top membrane.

It has been shown that a structure can go into resonances when the vibratory stimulus is presented right, under this principle we know that it is possible to induce vibration of the guitar with a small vibrator or a loudspeaker. As the vibration frequency increases slowly, from the source, one can clearly hear the call or A0 Helmholtz resonance and then the first top plate resonance. If this continues to increase at higher stimulation frequencies, then it will be higher than the resonance. The vibration patterns of the higher resonances can manifest membrane stretched over a set of parts in the case of the guitar up to the top. A form of power show the presence of the vibration modes presented using small piece of material that are much lighter which range from small pieces and wood, bits of cork or seed, spread evenly over the membrane. The membrane is subjected to vibration from the sound source. In the Figure 4 the Vibration Modes of the classical Guitar can be observed.

The characterization of the excitation modes is among the most used signals in systems theory which can be a sinusoidal force or impulse, in the particular case and the nature of the test signals was chosen sinusoidal source. Detection methods include: the distribution patterns in certain material distributed over the top, the measurement of acceleration with an accelerometer, the determination of the deviation by means of holographic interferometry and identification of the nodes with models Chladni (Claudia et al., 1997; Gougha, 2007).

There have been various studies and comparisons which analyzes the modes of vibration applied to the guitar, and one example was the publication by Curtu et al. (2008) which focuses on a comparative table of the modal analysis of the guitar work of different authors (Wright, 2005).

One literature report which presents the full modal analysis soundboards in (Bader, 2005) Table 1 presents a comparison among results of two different authors and the results performed by a finite element method which is discussed in the course of this study.

MECHANICAL ANALYSIS

Wood is a very complex material to analyze which to date has been one of the important points for the development and formalization in the manufacture of musical instruments. Having a microstructure, this is reflected in the macroscale of its own grain. Cell walls are layered and contain three organic compounds: adhesive cellulose, hemicellulose and nature of lignin (Jaroslav, 2005). The arrangement of the cellulose fibers in the wall is complex but important because it represents the part of the large anisotropy of wood. In this regard, the complexity of its structure can be compared with each cover has its own characteristics and personality of each individual.

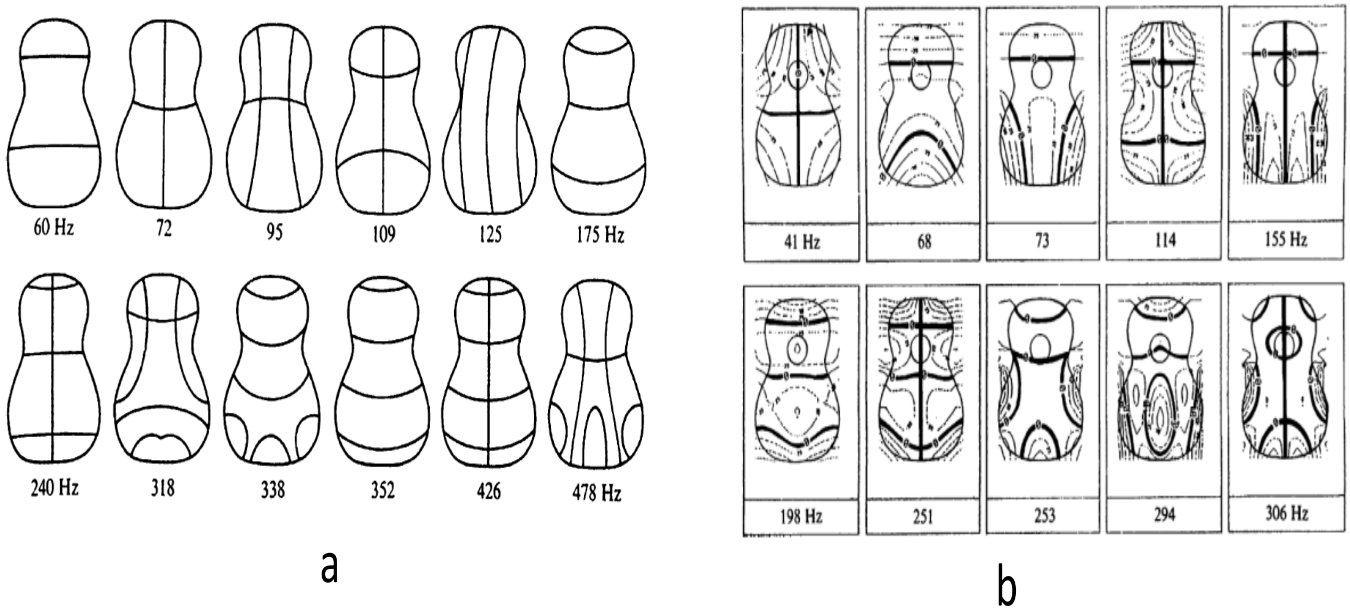


Figure 4. Vibration modes of the classical guitar from rossing (2010). a) Without brace (Rossing 1982), b) with traditional fan brancing (Richardson and Roberts, 1985).

Table 1. Relationship among the first five frequencies corresponding to the vibration modes (Bader, 2005).

Vibration mode	Richardson	Rossing	FEM
1	41(0,0)	163(0,0)	230(0,0)
2	68(0,1)	276(0,1)	369(0,1)
3	73(1,0)	390(1,0)	495(1,0)
4	114(0,2)	431(0,2)	502(0,2)
5	155(1,1)	643(1,1)	707(1,1)

Mechanical properties of wood have a highly variable behavior, which depends on the aging of the material, temperature, humidity or load. The linear relationship is observed in longitudinal and transverse tension, compression and shear stress-strain relationship is not linear (Recep and Sami, 2010). The constitutive models of wood materials that are implemented in manufacturing are nonlinear models which can be analyzed using finite element.

At the microeconomic level, the form of fiber, cell wall thickness, etc., should be included in the model. The certain continuous properties can be derived by using a process of homogenization and finite element method. The stiffness, shrinkage, and finally, the constitutive model is determined at different levels and then used in numerical simulations using CAD software.

For dynamics structures of complicated geometries described by higher order differential equation which do not lend themselves to solutions in closed form (Eyup, 2011), numerical methods such as finite difference method (FDM) and finite element method (FEM) are used to obtain solutions. For FEM, the structure is subdivided into a mesh or grid, which depends on the geometry, and it consists of one-dimensional line elements and two-dimensional area elements, such as, triangles of rectangles, or three-dimensional volume elements, such as, regular or irregular tetrahedral or other polyhedral. Node points on the boundaries of these elements are used as discrete points on the structure under investigation. The dependent variables used in the equation systems are defined only at these node points. For a two-dimensional plate, for example, the dependent variables would give the displacement, which would only be known at the node points of the mesh. In addition to the structural and dimensional geometry and the mesh identification, mechanical proprieties such as density and elastic constants including Young’s modulus, Poisson´s ratio and shear modulus, as applicable, are needed along with appropriate boundary conditions. In this case, tetrahedral elements are used to model the structure of the guitar, these elements are part of the corresponding volume mesh, which allows for proper results, which can be improved using a finer mesh size, so that the number of elements generated in the volume is increased and this refinement was done in the area of greatest interest in the study, which allowed us to obtain better results. The elements used are most commonly defined as isoparametric elements. Here, an “Ideal” element is defined with its own local coordinate system ranging normally from -1 to 1 as convenient integration and differentiation boundaries. Interpolation functions are defined in a way that when using the values of dependent variable, that is, the displacement of a plate, a continuous surface is achieved. So, for example, if a tetrahedral element were used, the element functions would be given as:

$$N_1 = 1 - \xi - \eta - \zeta$$

$$N_2 = \xi \qquad (13)$$

$$N_3 = \eta$$

$$N_4 = \zeta$$

Here, ξ, η, and ζ are local coordinate variables for the x-, y-, and z-direction and the element is defined for the Equation 14.

$$-1 \leq \xi, \eta, \zeta \leq 1 \qquad (14)$$

This element has the advantage, that it can be precisely integrated analytically once for all elements used. In each element, there must be a transferred from the local to the global coordinate system using a Jacobian matrix.

$$\mathbf{J} = \sum_{i=1}^{n} \mathbf{X}_i \frac{\partial \mathbf{N}_i}{\partial \Xi} \qquad (15)$$

Where Ξ= {ξ,η,ζ}, n=4 since there are four shape functions, and $\mathbf{X}_i$ are the coordinates in the global coordinate system, which is also called the reference frame. In addition to specify the differential equation system, only the displacement at the node points needs to be known to obtain a complete interpolation solution for the geometry. This leads to a simple linear equation system which can be solved. For structural mechanics, the differential equation system is often based on a stress-strain formulation like.

$$\sigma = E\varepsilon \qquad (16)$$

Where σ is the stress, ε is the strain, and *E* is the Young´s modulus. With higher dimensional problems, a matrix C is used, which are the material matrix describing Young´s modulus, the Poisson ratio and the shear modulus. When using a three-dimensional model, this matrix is:

$$C = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{(1-\nu)^2} & \frac{\nu}{(1-\nu)^2} & 0 & 0 & 0 \\ \frac{\nu}{(1-\nu)^2} & 1 & \frac{\nu}{(1-\nu)^2} & 0 & 0 & 0 \\ \frac{\nu}{(1-\nu)^2} & \frac{\nu}{(1-\nu)^2} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)^2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)^2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)^2} \end{bmatrix} \qquad (17)$$

Here E is the Young´s modulus, which can also be formulated as differential for all three directions, and ν is the Poisson´s ratio. Since the dependent variable is the displacement, the stress-strain equation can also be reformulated as:

$$\mathbf{D}\,\mathbf{C}\,\mathbf{D}_{\varepsilon}\mathbf{u} = \mathbf{F} \qquad (18)$$

Where

$$\mathbf{D} = \boldsymbol{D}_{\varepsilon}^{T} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \qquad (19)$$

is the differential matrix, F is an external force vector on each node point, and u is the discrete displacement vector.

$$\mathbf{u} = \{u_1, v_1, w_1, \ldots u_m, v_m, w_m, u_n, v_n, w_n\}^T \qquad (20)$$

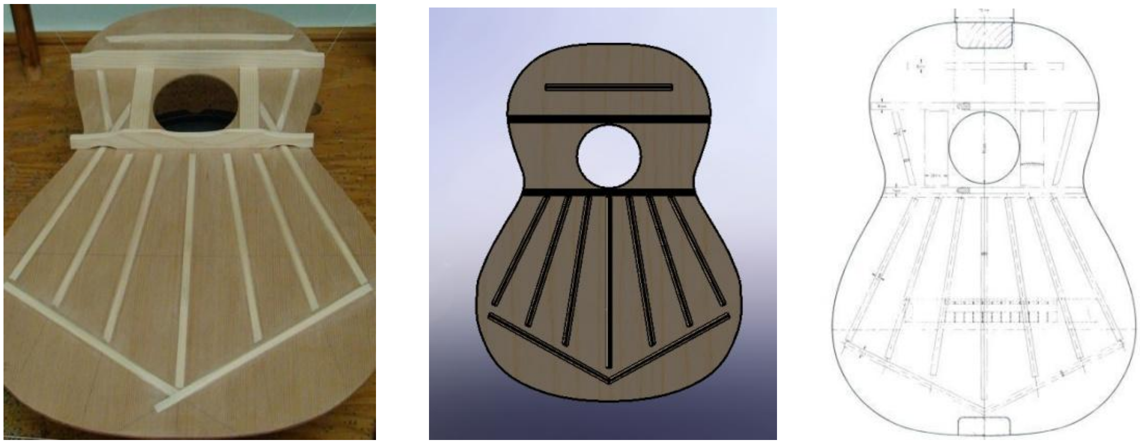
Here, u is the displacement in the x-direction, v in the y-direction and w- in the z-direction. If a matrix containing the shape functions of the isoparametric element, it is defined in the local frame as:

$$\mathbf{H} = \begin{bmatrix} N_1 & N_2 & N_3 & N_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & N_1 & N_2 & N_3 & N_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & N_1 & N_2 & N_3 & N_4 \end{bmatrix} \qquad (21)$$

Then a matrix of the derivatives can also be formulated as

$$\mathbf{B} = \mathbf{D}^{T}\mathbf{H} \qquad (22)$$

With the recent introduction of theoretical and computational techniques by using analysis software like Computer Aided Design and Computer Aided Engineering (CAD/CAE), it is possible to determine its natural frequencies and vibration modes of a guitar (Rubén et al., 2009; Shlychkov, 2001). Some commercial software includes; ANSYS, NASTRAN, COMSOL, etc. These tools are based on the FEM and describe the technique with an example made in ANSYS. The use of



a b b

Figure 5. The guitar top considered for this work. a) Construction of the guitar top, b) CAD model of the guitar top, c) sketch of the of the guitar top.

Table 2. Mechanical properties of wood "Sitka-spruce", considered in the FEM simulation.

Ex GPa	Ey MPa	Ez MPa	Gxy MPa	Gxz MPa	Gzy MPa	vxz	vxy	vzy
10.89	468.27	849.42	664.29	696.96	32.67	0.372	0.467	0.435

ANSYS is necessary due to the fact that the previously described properties can be modeled and a more robust and reliable modal analysis can be carried out; ANSYS used for the formulation of methods of approximation, which are selected according to the type of problem to solve, in this case, the method of extraction of Block Lanczos vibration modes was used, which allows faster convergence and better results. As a case study, a guitar cover top is used, shown in Figure 5. Here, the sketch, as well as the CAD model is presented. Later, ANSYS software was used by considering the wood material properties, and its mechanical properties are listed in Table 2 (Casado et al., 2007). The results of simulation by using a finite element analysis for the first four modes are presented in Figure 6.

EXPERIMENT

Once the analysis and finite element simulation (FEM) of the top of the guitar as shown in the previous section and Figure 6, it is important now to move to the phase of experimentation which allows us to observe a practical way different modes of vibration that occur at the top of the guitar at various stages of construction of the instrument, we have for example in the first stage experiments were conducted with the top mouth had no poles and no previous work the builder. In the next stage experiments were conducted with the top of the guitar with 5 and 7 bars proposed by Antonio Torres (Figure 2) and thickness change work conducted by the Luthier. In the other stage was added to the top of the guitar arm and ribs as seen in Figure 7. This experimental work allowed seeing development and performance of the modes of vibration of the guitar as analyzed in (Thomas and Graham, 2010). In the experimental treatment, the two most common types of wood in the manufacture of guitars are cedar and spruce.

The experimental technique used to obtain these frequencies through a preamplifier connected to a generator that can vary from 20 to 20 000 cycles per second. It is important to keep the top that will resonate with one of its nodal points, where there is no vibration and can easily be determined. This experimental technique is known as Chladni method which has been seen in the previous sections and some applications to the design and construction of guitars (Claudia et al., 1997).

Analysis software helps determine the natural frequencies of experimental shape to justify the results with those obtained computationally, in order to understand the behavior of the guitar in the future to improve the sound quality of the instrument.

This can also be helpful to somehow direct the work the builder is doing on each of the covers of the guitar.

In the last stage was manufactured experimental guitar is strung and made recordings for the sound for each string.

The Table 3 shows the values of the string properties used in the final stage. These properties are reported and used in the section of results.

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RESULTS

As expected, the full analysis of the guitar is a complicated process that is highly nonlinear, mainly due

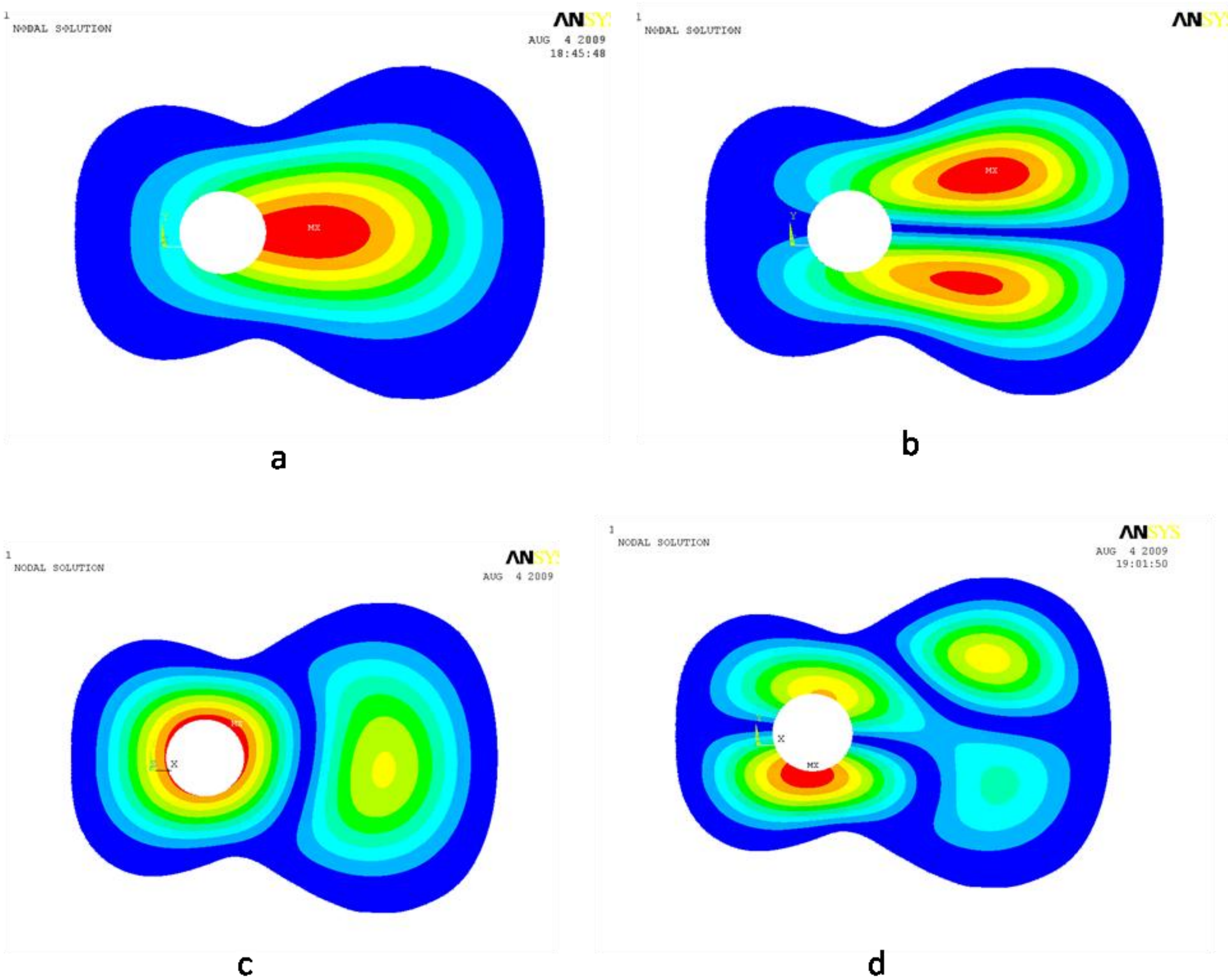


Figure 6. Finite element analysis. a) First mode; 193.8 Hz (0,0), b) second mode; 306 Hz (0,1), c) third mode; 360 Hz (0,2), d) fourth mode; 552 Hz (2,0).

to the characteristics of the wood. Figure 1 proposed a scheme based on some previous work that allows us to understand the simple behavior guitar to sound generation.

Figure 8 shows other results of this work, which involves measurement and simulation of different modes of vibration of the guitar in different stages of construction, and somehow allowing documenting and tracking the various stages of manufacture of the instrument.

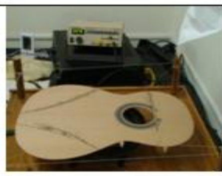
Table 4 shows the comparison of the vibration modes of classical guitars, where the guitar Kohno and Conrad were analyzed in the paper presented by Thomas et al. (2010). One way to validate the results obtained in this work is to make a comparison of these two guitars on the development and corresponding simulation of the guitar finished product. Another comparison that could be done with the results obtained are presented by Curtu et al. (2009) shown in the first mode at 128, the second at 143 and the third at 242 Hz.

In the final stage of rope up the guitar using a set of strings with the characteristics presented in Table 3, we observe the voltage frequency and mass of each of them, and later made records of the guitar designed.

In Figure 9 can observe from Figure 8 the behavior of the frequency and time evolution of each of the strings of the guitar after performing digital signal processing by applying the FFT.

DISCUSSION

The effect of the vibration modes of musical instruments has been very helpful in their manufacture process, one

Top		The vibration modes	
cedar		(0,0)	19 Hz
		(0,1)	38Hz
		(1,0)	44Hz
		(0,2)	318Hz
		(1,1)	----
		(2,0)	400Hz
		(1,2)	915Hz
cedar		(0,0)	25Hz
		(0,1)	55Hz
		(1,0)	72Hz
		(0,2)	402Hz
		(1,1)	-------
		(2,0)	-------
		(1,2)	1115Hz
cedar		(0,0)	30Hz
		(0,1)	55Hz
		(1,0)	74Hz
		(0,2)	350Hz
		(1,1)	438Hz
		(2,0)	558Hz
		(1,2)	816Hz

Top		The vibration modes	
Spruce with seven bars		(0,0)	30Hz
		(0,1)	43Hz
		(1,0)	52Hz
		(0,2)	72Hz
		(1,1)	490Hz
		(2,0)	560Hz
		(1,2)	730Hz
Spruce Without brace		(0,0)	90Hz
		(0,1)	330Hz
		(1,0)	295Hz
		(0,2)	360Hz
		(1,1)	750Hz
		(2,0)	------
		(1,2)	1050Hz
Spruce With brace and ribs		(0,0)	102Hz
		(0,1)	360H
		(1,0)	309Hz
		(0,2)	410
		(1,1)	570Hz
		(2,0)	680Hz
		(1,2)	1100Hz

Figure 7. Different testing stages of the guitar to obtain the vibration modes.

Table 3. String properties for D'Addario Pro Arté "composites, hard tension" guitar strings with a scale length of 0.65 m form (Woodhouse, 2004).

String	1	2	3	4	5	6
Tuning note	E	B	G	D	A	E
Frequency (Hz)	329.6	246.9	196.0	146.8	110.0	82.4
Tension (N)	70.3	53.4	58.3	71.2	73.9	71.6
Mass/unit length(g/m)	0.38	0.52	0.90	1.95	3.61	6.24
Wave speed (m/s)	429	321	255	191	143	107
Wave impedance(N s/m)	0.164	0.166	0.229	0.373	0.517	0.668
Bending stiffness (N m)	130	160	310	51	40	57×10 "6

Figure 8. Obtaining the four modes on guitar vibrated in the final stages of manufacturing.

Table 4. Comparison among the different vibration modes between two guitars; the simulated and the constructed.

Top plate	(0,0)	(0,1)	(1,0)	(0,2)	(1,1)	(2,0)	(1,2)
Kohno	183	388	296	466	558	616	660
Conrad	163	261	228	382	474	497	
Guitar simulation	193	306	260	360	552		
Guitar measurement	214	316	230	338	550	618	916

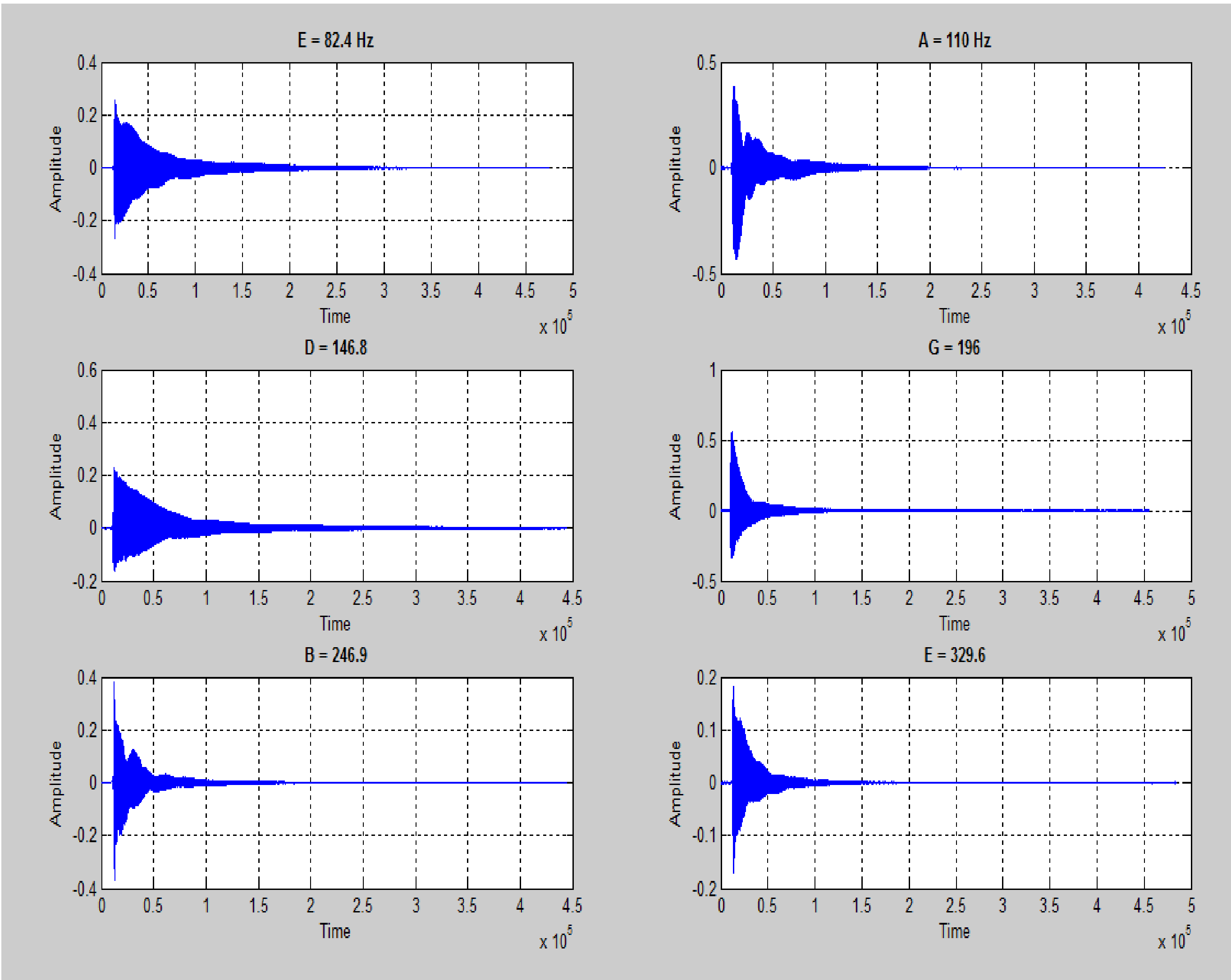


Figure 9. The evolution of sound and the strings in time.

example is the construction of violins which is where the original research was conducted on the effect of different modes of vibration and the studied important tools such as Guarnerius, Amati Stradivarius. It is now important to extend these studies to understanding the analysis and design of building classical guitars.] On the other hand, it would be interesting to see the effect of vibration modes in the new materials used in the construction of the lattice guitars, guitars double top with nomex. In conducting this research, it was observed that the vibration modes were very similar. One possible cause may have been in the builder's experience in which he said that he had to work on the top of the guitar in a certain way. It would be interesting to repeat a similar experiment with different builders as you can probably find a significant change in the vibration modes thus leading to some independence from material used in connection with the way you work.

Another important point would be to develop a methodology which includes the modes of vibration, the materials, the compression of air due to the vibrations of the upper and lower lid, so that theoretically, certain sound characteristics of the instrument can be predicted.

Conclusions

One of the main factors that determine a better approach in the design and construction of an instrument such as acoustic guitar is the development of mathematical models and computer simulation primarily on the knowledge of the mechanical properties of wood as shown in Table 2. The development and validation of the vibration modes of the different stages of construction gave the manufacturer a way to assess the sound quality of the instrument.

The development of a computational model in which we can consider the characteristics of the wood anisotropies, integrate aging factors such as elasticity and other features that are not evenly and uniformly on all wood plaque may predict a better accuracy for the behavior and modes of vibration so that the builder can consider certain features before moving to the production of each instrument.

This work presented the conclusion of a series of several experiments which tested cedar top and top spruce. Cedar guitar was made with the specified characteristics. The final result of vibration modes was very similar in all cases.

Caps were manufactured in different geometric structures in the 7 bar guitar known as a fan. One of the important results of all these experiments is a square structure alteration in the modes of vibration. The best response obtained was a round structure which is used most in the manufacturing of guitars.

Another result is the slight alteration of one of the bars as shown in Figure 2a which allowed a certain way to improve the vibration mode by changing the thickness of the cover and on the other hand increase the general resistance by preventing fractures.

The comparison of the modes of vibration of the guitar made with respect to previous studies such as those shown in the comparison table of the results on guitars recognized as Kohno, helped to validate in some way a part of the work.

A topic for future work is the effect of the vibration modes of different distribution on the bars used in top manufacturing, though other works could be presented. In the analysis of different thickness along the plate which consists of the top of the guitar and thickness in most cases, the manufacturer determines the manufacturing of guitars according to their experience heuristically.

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