Modal Analysis of a Brazilian Guitar Body

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The Brazilian guitar is a countryside musical instrument and presents different characteristics that vary regionally by configuring as a sparse group of string musical instruments. Basically, the instrument diversity comes from different geometries of resonance box, shapes of sound hole, types of wood, different tunings, and number and arrangement of strings. This paper intends to present the numerical and experimental modal analysis of a Brazilian guitar, without strings, in a free boundary condition. The modal analysis technique is applied in the determination of the natural frequencies and the corresponding mode shapes. The main dimensions of an actual Brazilian guitar body are used to build the computational model geometry. The numerical modal analysis uses finite element method (FEM) to determine the dynamic behavior of the vibroacoustic system, which is composed by the structural and acoustic systems coupled. The experimental modal analysis is carried out in an actual Brazilian guitar body, where the structural modal parameters (frequency and mode shape) are extracted and used to update the numerical model. Finally, numerical and experimental results are compared and discussed.

1 Introduction

The relationship between measurable physical properties of a musical instrument and the subjective evaluation of their sound quality and performance is an important subject of musical acoustics research. Therefore, analytical and numerical methods have been employed to predict and describe accurately the vibroacoustic behavior of complex systems like plucked string instruments [1-4]. With the advent of technology and consequent improvement of the computational processing, numerical models have been used to simulate complex systems and to calculate modal parameters (natural frequency, damping rate and mode shape), which have substantial effect over the tone and sound power desired for a musical instrument [5]. Hence, simulation tools seem to be valuable for the musical instrument design. In general, the *luthier*, a craftsman who makes or repairs lutes and other string instruments, do not have this facility. In the building process it is required to deal with different types of wood, with well-defined characteristics, which makes impractical this type of investigation.

Experimental tests and numerical simulations by Finite Element Method (FEM) have been previously applied to obtain modal parameters for the classical guitar [1, 2, 6-10]. However, very few have been founded for others types of guitar [2, 4, 11]. In a previous paper [12], the authors presented an application for a numerical modal analysis of a Brazilian guitar resonance box.

This paper presents a numerical and experimental modal analysis of a Brazilian guitar, without strings, in a free boundary condition. The main dimensions of an actual Brazilian guitar body are used to build the computational model geometry. The numerical modal analysis uses ANSYS-FEM to determine the dynamic behavior of the vibroacoustic system, which includes the structural (wood components) and acoustic (fluid inside guitar box + sound hole) systems coupled. The experimental modal analysis is carried out in an actual Brazilian guitar body, where the structural modal parameters are extracted by Polymax method and used to update the numerical model. Finally, numerical and experimental results are compared and discussed.

2 The Brazilian Guitar

Par excellence, the Brazilian guitar is a countryside musical instrument. It presents different characteristics that differ regionally, by configuring as a sparse group of string musical instruments. Basically, the instrument diversity comes from different geometries of resonance box, shapes of soundhole, types of wood, different tunings, and number and arrangement of strings. However, this diversity regards to different Brazilian cultural expressions in which this musical instrument is seen as a ritualistic tool. Thus, the expression "Brazilian Guitar" is capable to qualify the instrument in all its variations. According to Corrêa [13], there are six great groups of this instrument: *viola caipira* (or *viola cabocla*), *viola de cocho*, *viola de buriti*, *viola machete*, *viola nordestina* and *viola de fandango*. This paper is focused on *viola caipira*, which is the most known and played in all regions of Brazil, particularly in the Southeast and Midwest regions. The *viola caipira* is derived from the Portuguese guitar, which arrived in Brazil through the Portuguese settlers from different regions and has passed to be used by the Jesuits in the Indian catechesis [14].

Generally, the *viola caipira* has 10 strings combined at five pairs. Two pairs are tuned in a sharp note on the same fundamental frequency, i.e., the same note at the same height (unison), while the remaining pairs are tuned to the same note, but with a difference of one octave in the height (rate 2:1). The main external parts of a *viola caipira* are similar to a classic guitar, as shown in Fig. 1a.

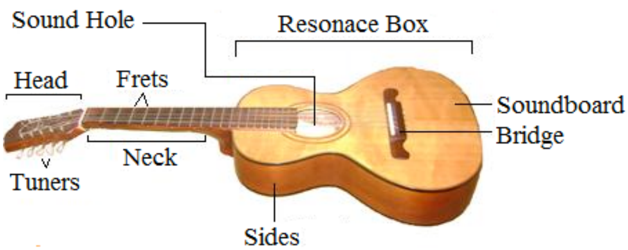


Figure 1: Main external parts of a Brazilian guitar.

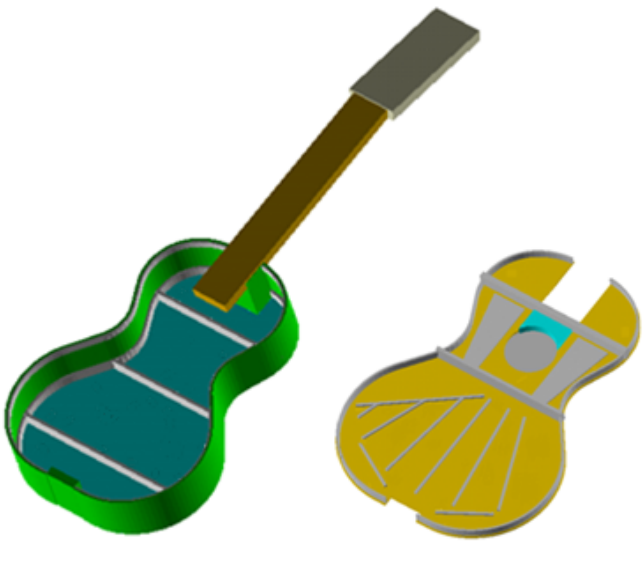
The resonance box is composed by top plate (soundboard), back plate, sides and internal structures. These parts enclose the acoustic cavity, which communicates with the external air through the sound hole. The strings are attached to the soundboard through the bridge. Inside the resonance box (Figure 2) there are also fixtures and reinforcements, so as to soundboard harmonic braces; sound hole plates; braces; lining; neck and tail blocks.

Different types of wood are used for the soundboard. In general, *luthiers* and manufacturers use German Spruce (*Picea alpestris*), Pau-Marfim (*Balfourodendron riedelianum*) and Sitka Spruce (*Picea sitchensis*). There are countless types of wood used for the back plate and sides. Common options include Pau Ferro (*Machaerium scleroxylon*), Imbuia (*Ocotea porosa*), Brazilian Mahogany (*Swietenia macrophylla*), Cedar (*Cedrus*), Brazilian

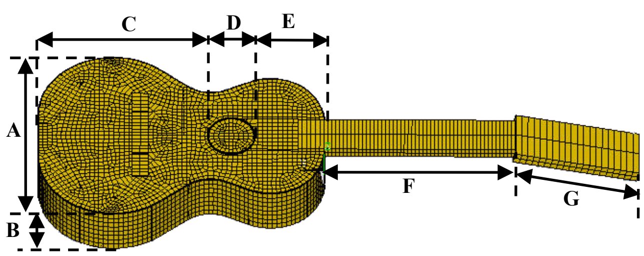
Rosewood (*Dalbergia nigra*), Indian Rosewood (*Dalbergia sissoo*), the latter being the most widely used today. Usually, the neck of guitars is made of Cedar, Mahogany or Red Oak (*Quercus rubra*) and the neck and tail blocks are made of the same wood of soundboard. The scale is generally made of Ebony (*Diospyros mespiliformis*) or Pau Ferro. The tuners are composed by plastic buttons and tuning keys made of nickel, brass or steel. The frets are made of steel or brass. Usually, there are *violas caipira* with scales of 10 to 22 frets. It is not possible to establish with accuracy, a standard size for *viola*. Some have very small size, such as the *viola machete* (from Bahia). Others are intermediate-sized and large size (from Paraná). Roughly, it is possible to find sizes between 30 and 50 cm for the length of the largest bulge [13].

3 Numerical and Experimental Modal Analysis

The numerical simulations of the Brazilian guitar body were implemented using the ANSYS-FEM software (release 13.0), which offers the possibility to obtain the vibrational behavior of complex mechanical structures. The geometry of the instrument body was designed using the parts and dimensions of a commercial *viola caipira*, brand *Rozini*, and model *Ponteio Profissional*. Figure 2 shows the guitar main dimensions and the components included in the numerical model.



(a) Back Plate and Sides (b) Soundboard



A	B	C	D	E	F	G
319	83	301	71	98	300	200

(c) Dimensions [mm].

Figure 2: Internal parts in numerical model: (*a*) back plate and sides; (b) soundboard; and (c) main dimensions and discretization.

The difficulty to identify some wood types led to assume indications from the literature [16]. Same when it was possible to identify the wood component was not found its mechanical properties, leading to the use of similar timber properties. Thus, it is assumed that the soundboard, tail block, neck block and internal reinforcements are made of Sitka Spruce (*Picea sitchensis*). The back plate, sides and neck-soundboard junction are made of Yellow Birch (*Betula alleghaniensis*). Neck and head are made of Red Oak (*Quercus rubra*). Tuners and frets were not included. Table 1 shows the mechanical properties of woods used in FE model. The thicknesses of soundboard, back plate and sides are 3.0 mm, 3.5 mm and 2.0 mm, respectively.

Table 1 – Wood mechanical properties.

	Sitka Spruce	**Yellow Birch**	**Red Oak**
E_x [MPa]	10,340	11,320	14,110
E_y [MPa]	800	880	2,219
E_z [MPa]	440	560	1,181
G_{xz} [MPa]	660	830	1,282
G_{xy} [MPa]	630	760	1,167
G_{yz} [MPa]	30	190	-
ν_{xz}	0.372	0.426	0.350
ν_{xy}	0.467	0.451	0.448
ν_{zy}	0.435	0.697	0.560
ρ [Kg/m^3]	460	668	700

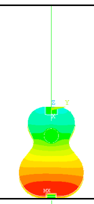
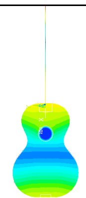
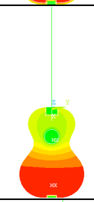
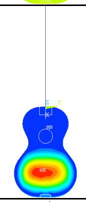
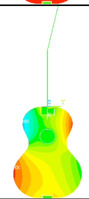
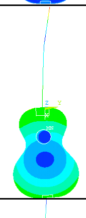
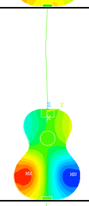
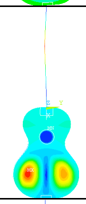
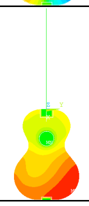
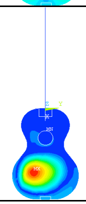
Vibroacoustic numerical model considers the body structure without strings with the cavity filled with air (internal acoustic model). The ANSYS structure is modelled with SHELL63 element for plates, BEAM188 element for beams and SOLID65 element for solids as tail and neck blocks. The air inside resonance box is modelled with FLUID30 element. Except for the beam element all other elements use orthotropic material model. Fluid-structure interaction is obtained with the coupling matrices, which lead to an asymmetric matrix eigenproblem solution.

A mapped mesh (Figure 2c) is constructed in solid and fluid geometries, which contains around 22,600 elements and 19,000 nodes. Mesh discretization allows response up to 1000 Hz. [17]. A vibroacoustic modal analysis is performed with structural free boundary condition and null pressure in the sound hole.

Table 2 shows the first 5 numeric natural frequencies and mode shapes for the soundboard. Qualitatively the results are consistent with that founded in literature for classic guitars, and also demonstrated by the authors in previous paper [19].

Experimental test used in this work is the Experimental Modal Analysis (EMA) technique [18]. The Frequency Response Functions (FRFs) are obtained through SISO (single-input-single-output) measurement techniques in a free boundary condition at the normal direction to the soundboard. Force excitation is provided by a small electrodynamics shaker, through the stinger and the force transducer, located on the bridge (Figure 3). The force transducer was attached to the bridge with superglue.

Table 2 – First 5 numerical vibroacoustic modes of the Brazilian guitar body.

f [Hz]	**ACOUSTIC PRESSURE**	**STRUCTURAL DISPLACEMENT**
78		
143		
151		
262		
278		

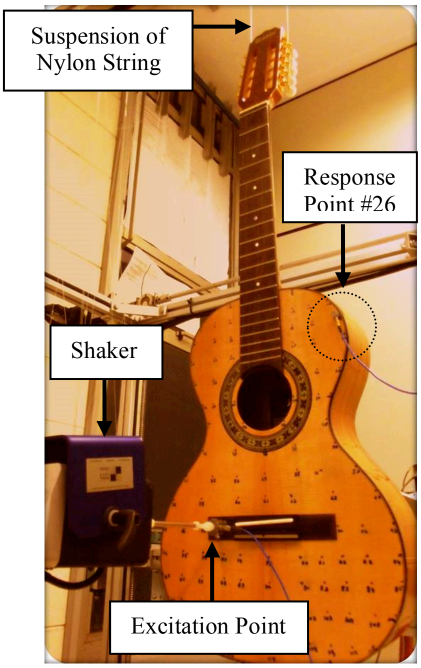


Figure 3: Experimental setup used in the modal analysis of the Brazilian guitar body without strings.

Excitation point at the bridge was choosing to avoid nodal regions, at least for the first five modes. Response measurement points were distributed as following: 111 points on the soundboard, 118 points on the back plate and 10 points on the neck and head. The experimental point coordinates are coincident as the FE model coordinates.

Both excitation and response measurements are in the normal direction to the plates. The excitation signal is a periodic *chirp* in a frequency range of DC-20kHz. The response is obtained from an accelerometer, which is attached to the successive points by a thin wax layer. Table 4 presents the measurement equipment used.

Modal analysis was conducted at a frequency range from DC-1024 Hz with a 2.0 Hz resolution was used. For each measurement point, 50 averages were automatically calculated with 75% overlapping. The FRFs measurements were performed using LMS TestLab, and the modal parameters were obtained by LMS Polymax.

Table 4 – Measurement Equipment

Device	Model	Range	Sensitivity
Accelerometer	PCB 352C65	0.5Hz-10kHz	0.15 [mV/m/s^2]
Force sensor	PCB 288D01	0.7Hz-7kHz	9.97 [mV/N]
Shaker	TMS K2004E01	up to 31 N	----------
FFT Analyzer	LMS Scadas SCR05	-----------	----------

4 Results and Discussions

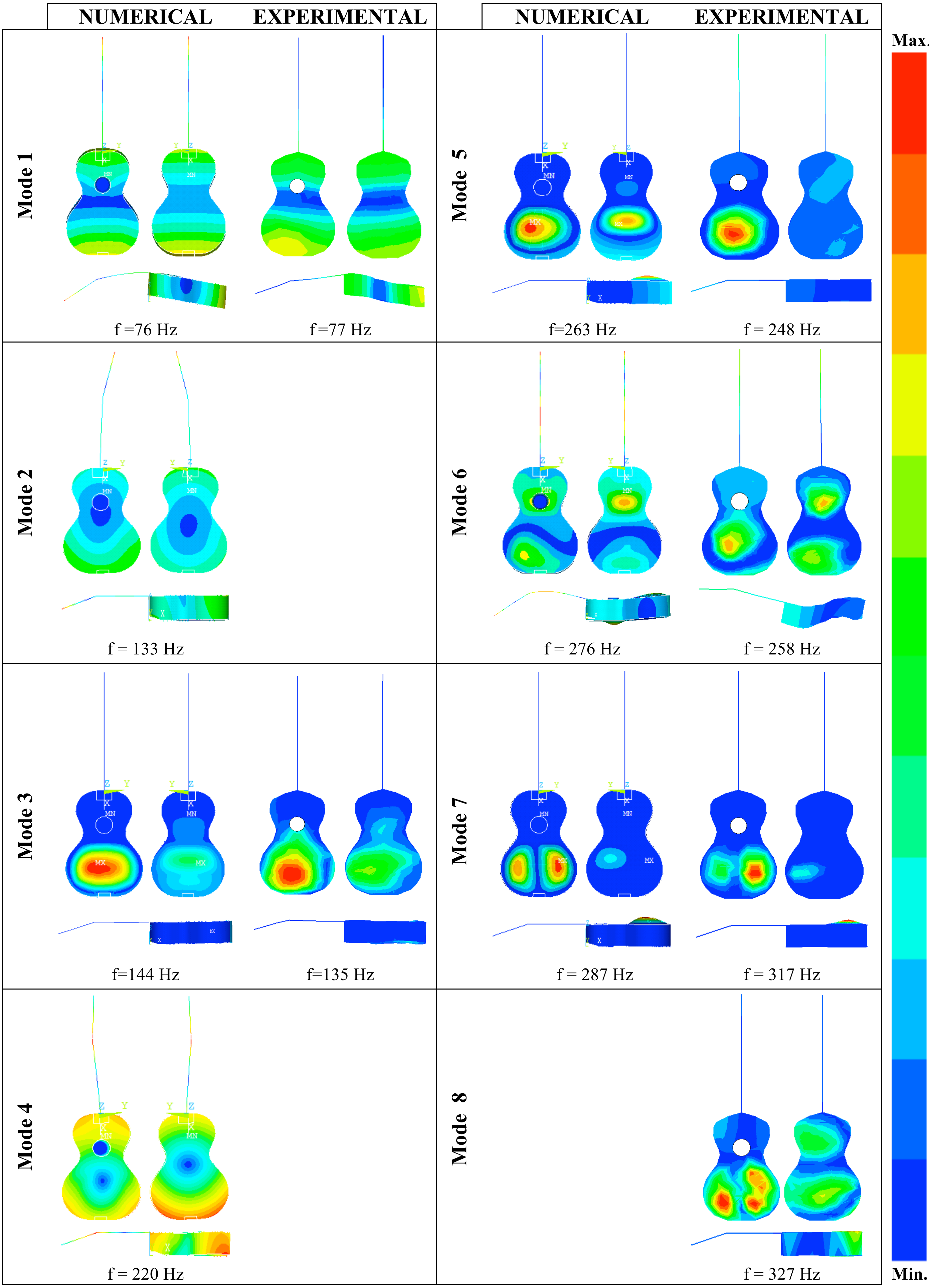
In order to compare the experimental results with the numerical ones, the computational model was updated varying the mechanical properties of woods (elastic modules and density). Table 4 presents the comparison of the firsts 8 structural natural frequencies and mode shapes obtained with the numerical vibroacoustic updated model and the experimental measurements on Brazilian guitar body.

Modes 2 and 4 were not obtained in the experimental results. This happens because these modes are predominantly lateral displacements, which could not be detected by the uniaxial accelerometer used to measure only displacements normal to the soundboard.

Soundboard numerical modes 1, 3, 5 and 7 and back plate numerical modes 1, 3, 6 and 7 are in good agreement with their corresponding experimental modes. However, soundboard numerical mode 6 and back plate numerical mode 5 seem to be in opposition of phase to their experimental modes.

Note that experimental modes 7 (f = 317 Hz) and 8 (f = 327 Hz) are not two modes as obtained with the shaker excitation (Figure 4). Tests performed with a hammer excitation shows that only one natural frequency actually should be identified in this region. The bifurcation in two different natural frequencies probably occurs because of added mass and inertia moment generated by the force sensor at the shaker excitation setup. In this frequency region the numerical model, which does not include the excitation setup, only presents the mode 7 (f = 287 Hz), as shown in Table 4.

Table 4 - First 8 natural frequencies and mode shapes obtained with the numerical updated model and the experimental measurements.



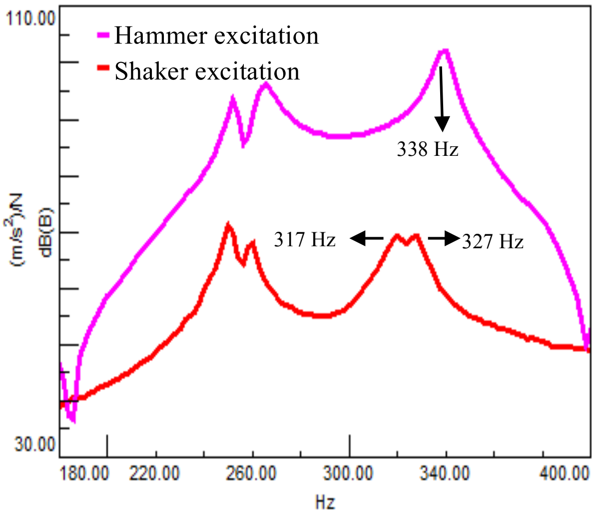


Figure 4: FRF curves (acceleration) obtained through hammer excitation (▬) and shaker excitation (▬) for the same excitation and response points.

The identified modes 1 and 6 behave as guitar body global modes, which are similar to the flexural beam modes. Mode 1 looks like the first bending mode of a free-free beam and mode 6 as the second bending mode. Identified modes 3, 5, and 7 behave as guitar body local modes, which are plate modes. In general, the largest amplitudes are situated in the lower and middle zones of the soundboard and back plate for the analyzed frequency band. Mode 3 is the fundamental mode of the resonance box, where the soundboard presents an antinodes zone at the position of the bridge. The upper zone of the soundboard remains motionless due to the presence of the soundboard braces and neck block. In the mode 7 the back remains motionless: the internal reinforcements difficult the vibration of its transversal flexural patterns and thus the contribution to radiation due to the back will be negligible.

The results for the natural frequencies present errors ranging from below 7% (modes 1, 3, 5, 6) to almost 10% (mode 7), being the highest error the mode 7 (9.4%) and the lowest with mode 1 (1.0 %).

The disagreement between some results of natural frequencies and mode shapes can also be attributed to the simplifications assumed in computer simulation. Also, the lacquer layer and the truss rod and tuners were not considered in the computational model. The applied shaker excitation, force sensor and accelerometer modify significantly the experimental modal identification in relation to the real structure since they add mass and inertia moment o the guitar body in the region of the measurement point.

5 Conclusion

The Brazilian guitar was briefly described with regard to its historical, structural and acoustical characteristics. A procedure for vibroacoustic modal analysis by finite element method with ANSYS software was developed. The computational results were verified with experimental data obtained from an experimental modal analysis. In general, it was observed that the finite element method proved to be effective and can determine the dynamic behavior of the Brazilian guitar body. However, in order to get good results from the computational model and to minimize de model updating process, it is very important to identify and characterize the mechanical properties of all woods used. The influence of the excitation and measurements process is very important due to the guitar low weight and acoustic sensitivity. Future works are under way using impact hammer excitation and laser vibrometer measurements. Furthermore, it must be observed that the determination of the modal characteristics of the guitar body is only an initial stage about the study to obtain tones and sound power desired for stringed instruments. But, this information is a helpful tool for craftsmen and manufactures to get more control over the quality of the instrument in different stages of its construction. Finally, to go further in this research we need additional tests and psychoacoustic measurements of the sound field, which explain subjective evaluations and allow their relationship with objective parameters.

Acknowledgments

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