Invited paper

COMPUTATIONAL EVALUATION OF THE INFLUENCE OF THE SOUNDHOLE SIZE ON THE DYNAMIC BEHAVIOUR OF THE PORTUGUESE GUITAR

M. Vieira[1], V. Infante[1], P. Serrão[1], A. M. R. Ribeiro[1]

[1] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal

Abstract
The Portuguese guitar is a pear-shaped plucked chordophone particularly known for its role in Fado, the most distinctive traditional Portuguese musical style. The acknowledgment of the dynamic behavior of the Portuguese guitar, specifically of its modal and mode shape response, has been the focus of different authors. In this research, a computational evaluation of the influence of the soundhole size is produced, in order to evaluate the influence of this geometrical parameter on the dynamic behavior of the Portuguese guitar. The presented results allow for a better comprehension of these parameters and are of relevant importance for luthiers.

Keywords: Portuguese Guitar, Dynamic Behaviour, Coupled Model, Soundhole.

PACS no. 43.40.+s, 43.75.Gh

1 Introduction

Guitars have been the focus of several researchers and scientific projects over the last decades, much due to its widespread use around the world. The aim of this intense research is to understand the dynamic coupling between guitars' individual components and the relevance of each one to the radiated sound, which is, ultimately, the fundamental mission of a guitar. This comprehension of the dynamic behavior of the guitar represents a strong asset to luthiers and its crave to produce better musical instruments, and may be done in varied ways, ranging from experimental modal analysis to numerical models.
The Portuguese guitar is a national star and is directly descended from the European cittern, possessing a pear-shaped feature of the resonance box, six double-string courses, a characteristic tuning and requires a distinctive finger plucking technique in order to be played. The two more common models of the Portuguese guitar are the Coimbra and Lisbon ones, which will differ between each other from its general dimensions, the intrinsic tuning and the arm-end decoration: Coimbra guitar is usually longer, due to the bigger effective string length, it has a more resonant bass sound and the decoration near the tuning machine is tear-shaped, while for the Lisbon version, a more ornamented arm-end is used.

Because its use is almost confined to Portugal, there is a relevant lack of scientific knowledge about the Portuguese guitar; therefore, there is little understanding of the effective dynamic behavior of the Portuguese guitar, in contrast to the classical guitar, which has been the focus of innumerous studies and researches. Still, some relevant projects have been made and are presented next, [1], [2] and [3] amongst a few others.

Inácio, O. et al [1] performed experimental modal analyzes to ten different Portuguese guitars, having obtained the accelerance and the vibroacustic frequency response for each. The tests were made to both Coimbra and Lisbon guitars. A relevant result was obtained: tests were produced either with the soundhole opened or closed, and it showed that one of the lowest peaks (between 121 and 160 Hz) disappeared for the closed setup. This phenomenon (which became evident in all the tested guitars) is associated with the Helmholtz resonance, which is present in air chambers with an opening. With a closed soundhole, there is no opening to the outside air and, therefore, the mode does not appear. This mode is one of the most relevant for the total sound radiation of the guitars and confirms the high dependence of the modal response of the guitar with the air inside the chamber. This result, which has been noted by other authors, not only for Portuguese guitars but for classical guitars [4], [5] is a strong indicator that, for numerical models, to only consider the structural part of the guitar is not enough to obtain a confident model. During this research, a mapping of the top soundboard of one of the tested guitars was made, allowing the identification of three modes. A T(1,1) mode is identified at 275 Hz, a T(1,2) mode is identified at 360 Hz and a T(1,3) is present at 635 Hz.

In [3], Debut, V. et al propose a simplified finite element model for the top soundboard (and its respective reinforcements) of a generic Portuguese guitar, using CAST3M and considering the material as orthotropic. The results indicate a T(1,1) mode at 252 Hz, a T(1,2) mode at 400 Hz, a T(2,1) mode at 444 Hz and a T(3,1) mode at 560 Hz. This model is even more simplified than the one suggested by Vaz [6], meaning that the structural influences of the ribs, bottom soundboard and other parts of the guitar are not considered.

The presented models of the Portuguese guitar do not consider the air inside the chamber. Still, many authors have done similar researches for other types of guitars. For example, Paiva, G. [7] produced a vibroacustic model for the Brazilian guitar. The influence of the air inside the chamber was evaluated, having been concluded that, if not considered, the obtained results may (and depending on the goals of the analysis) possess relevant errors. With the inclusion of the air, new modes appeared and others, that were already present in the structural model, became asymmetric. The influence of the internal reinforcements inside the guitar box was analyzed too, showing that its disposal affects the higher frequency modes, whilst the low frequency ones depend more on the box geometry. A correlation with experimental data was, as well, made, with good correspondence up to 450 Hz.
Elejabarrieta, M. et al [8] studied the influence of air inside the air chamber of a classic guitar, using a coupled finite element model, and compared the obtained results with the experimental ones, describing, as well, each individual mode and the influence of air on it.

A research of the dynamic behaviour of the Portuguese Guitar has been made before [9], where a correlation between experimental and numerical data was produced. A coupled fluid-structural model was built. Results indicated good correlation for many experimental modal shapes, whilst few of them did not appear on the numerical results. The model developed during this research will be used in the present paper, serving as the standard model.
Obtaining confident results for this type of computational modal guitar analysis is quite difficult due to the complex geometries of guitars and the anisotropic characteristic of woods. Complex geometries arise from curved surfaces, purposeful asymmetry of different parts and difficulties identifying the exact position of reinforcements or the thickness of the soundboards and ribs, for example. On the other hand, woods possess an anisotropic behavior, which is due to the specific arrangement of cellulose on its layered cell walls [10]. Furthermore, woods have great importance on a guitar, not only due to its acoustic influence, but as well to guarantee the necessary structural resistance over the

time (especially on the high amplitude boards) and to respond to aesthetic requirements [11], [12]. Usually, and to ease this type of analyzes, woods are considered not as anisotropic but as orthotropic materials. The most important parameters that characterize woods are its Young modulus, density and respective Poisson coefficients, stability with humidity, heat bendability and hardness [10], [11], [13]. Damping takes special relevance as well, although it may be more difficult to evaluate and compare [11]. Generally speaking, the description and evaluation of a certain type of wood should be always made using statistical methods, due to its variations, even for the same species.
Although woods and its properties take special relevance in the created sound, it is the interaction between the strings and the soundboard the main mechanism behind this sound radiation [12], [14]. In fact, strings alone do not radiate much sound, being the top soundboard the bigger responsible for this sound radiation [12], while the air chamber and the bottom soundboard radiate less sound [12], [14], [15], because they have no direct connection with the excited strings and because the player provides dampening to their movement [15].
It is intended, in this project, to use the already built coupled vibroacoustic model of the Portuguese guitar [9], to evaluate the influence of the soundhole size on the computational dynamic behavior of the Portuguese guitar. The vibroacoustic model is based on a three-dimensional model of the Portuguese guitar, which is analyzed using a finite element software. This research represents an asset to the comprehension of the dynamic behavior of the Portuguese guitar since the understanding of the influence of different geometry patterns on the guitar may be of undoubtful use for guitar luthiers and related academic researchers.

2 Methodology

Almost all the guitar models used on finite element analyzes found on the literature are simplified; this is usually done to obtain a lighter finite element mesh, which will require less computational processing time, as well as to ease the modelling. So, many times, the decorate features of guitars, or even the fingerboards, are not considered. This may be acceptable since the air chamber and the top plate are the most important parts for the generation of sound; furthermore, classical guitars possess a simpler air chamber external shape, when compared to the Portuguese guitar: for example, the ribs of the classical guitars are usually perpendicular to both the soundboards; this is not true for the Portuguese model. In this project, three realistic modes were produced. One which had been already built [9], and two others, equal to this first one but with varying soundhole size. Although the model got heavier for finite element analysis, it was the only way to determine modes that are not directly (or only) related with the movement of the ressonant chamber. These modes, although not responsible for any sound generation, may be useful for the feeling the instrument passes to its player [16].
The used wood distribution for the developed models was:
1. Sitka-spruce for the top soundboard and internal reinforcements;
2. Mahogany for the ribs, bottom soundboard and arm;
3. Ebony for the fingerboard.
A generic isotropic bone definition was used for the two bone parts and a structural steel was used for the tuning machine and the fingerboard frets. Standard air properties were used for the chamber. The used properties are indicated on Table 1.

Table 1 – Material properties used for the FEM analyses.

	Young Modulus			Poisson Coefficients			Shear Modulus			Density
Material	E1 (GPa)	E2 (GPa)	E3 (GPa)	υ12	υ23	υ31	G12 (GPa)	G23 (GPa)	G31 (GPa)	(kg/m^3)
Sitka-Spruce	11.6	0.9	0.5	0.37	0.47	0.25	0.75	0.039	0.72	390
Mahogany	11.0	0.53	1.18	0.3	0.26	0.03	0.94	0.63	0.22	450
Ebony	16.9	2.11	0.95	0.3	0.26	0.03	1.67	0.4	1.12	900
Isotropic bone	17.0	-	-	0.3	-	-	6.50	-	-	1500
Steel	200	-	-	0.3	-	-	77.0	-	-	7850

The properties of the woods were retrieved from the Wood Handbook [13].

The three developed models are presented on Figure 1.

Figure 1 – Representation of the three developed 3-dimensional CAD models: at left: the original model (Model 2) [9], at the middle, the lower diameter soundhole model (Model 3) and. on the right. the higher diameter soundhole model (Model 1).

Model 1 has a soundhole with a diameter of 97 mm. Model 2 has 77 mm and Model 3 57 mm. Although the diameter variation is linear, this is not true for the soundhole areas, being 7390 mm^2 for Model 1. 4657 mm^2 for Model 2 and 2552 mm^2 for Model 3. The three models were analysed in a convenient FEM software. using a couple fluid-structural algorithm. These algorithms allow for the study of the coupled influence between fluids and structures. but result in heavier computational times. The generic characteristics of the developed FEM models (where one is represented on Figure 2) are presented on Table 2.

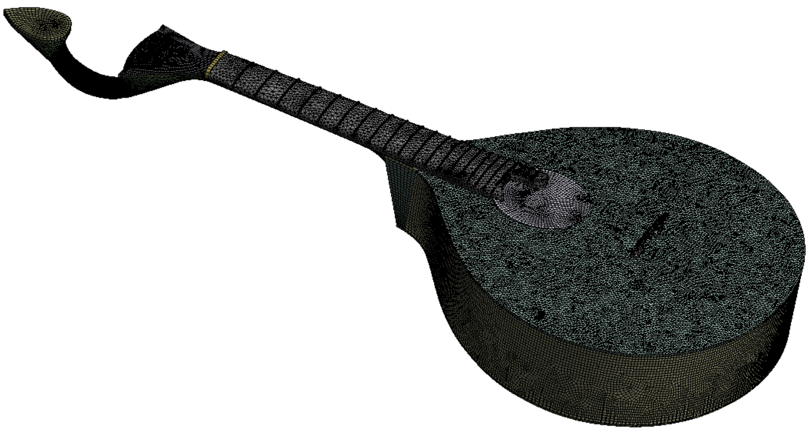

Figure 2 – Representation of the mesh for the Model 1.

Table 2 – Number of elements for each model.

	Model 1	Model 2	Model 3
Fluid elements	197634	193377	194878
Total elements	796314	784254	835274

The convergence of the results was guaranteed.

3 Results

The obtained results are presented in this section. The first four coupled modal shapes are presented, for the three developed models. The modes are ordered by the experimental results (which were previsouly obtained [17]). with the respective experimental modal frequency indicated for each individual mode. Modes are referred to as coupled, in the sense that they are retrieved from a coupled model, and not because coupling is fundamental for its appearance.

First Coupled Mode

The results for the first coupled mode (shown on Figure 3), which has an experimental value of 88 Hz [Octávio]. are indicated on Table 3 for the three models.

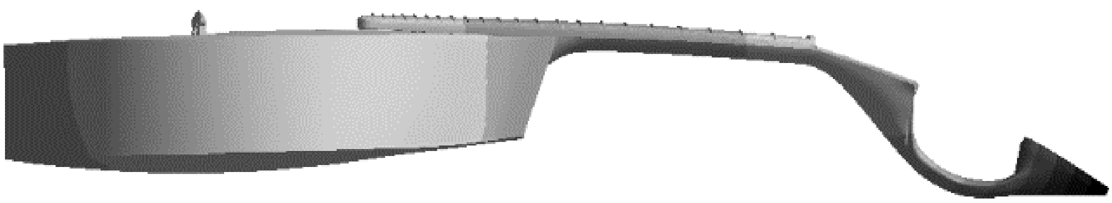

Figure 3 – Generic representation of the first mode, which appears on the three Models.

Table 3 – Numerical frequencies for the three Models.

	Model 1	Model 2	Model 3
Frequency (Hz)	89	89	83

This mode is not particularly influenced by the fluid inside the chamber [9], nor by the soundhole size. as it can be identified from Table 3. Still. Model 3 (with the lower diameter) has a small variation (from 89 Hz to 83 Hz). This is a bending structural mode, which is not responsible for relevant amount of radiated sound. but might be important for the vibrational sensations passed from the guitar to the player [16].

Second Coupled Mode

The results for the second coupled mode (Figure 4), which has an experimental value of 125 Hz. are presented on Table 4 for the three studied models.

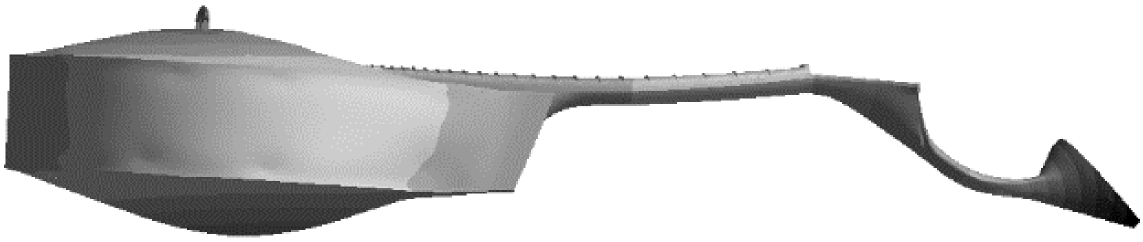

Figure 4 – Generic representation of the second mode.

Table 4 – Numerical frequencies for the three Models, on the second coupled mode.

	Model 1	Model 2	Model 3
Frequency (Hz)	164	155	135

This mode, a T(1.1), B(1.1), is particularly relevant for sound generation, and is usually referred to as the Helmholtz Mode (although it does not correspond to a true Helmholtz mode. as this mode would have to be characterized by no pressure variation on the air inside the chamber. which is not the case). This mode is particularly tricky. as it only appears on coupled analysis [9]. Experimental results, which were quoted before, have denoted, as well, that the presence of the soundhole is fundamental for the correct sound radiation caused by this specific mode.

Third Coupled Mode

The results for the third coupled mode (Figure 5), which has an experimental frequency of 280 Hz. are presented on Table 5 for the three developed models.

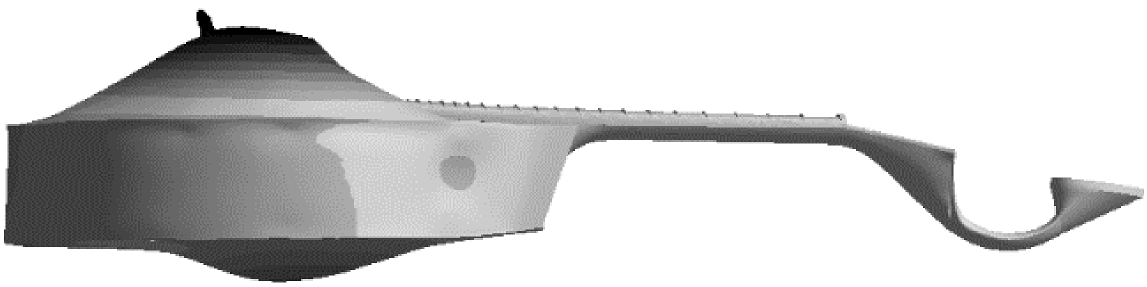

Figure 5 – Generic representation of the third coupled mode.

Table 5 – Numerical frequencies for the third coupled mode.

	Model 1	Model 2	Model 3
Frequency (Hz)	311	310	306

This mode, a T(1.1) B(1.1) too, is very similar to the second studied mode. Still, its shape is not dependent on the presence of the soundhole, as described by previous authors, and its frequency is not much affected by the soundhole diameter.

Fourth Coupled Mode

The results for the fourth studied mode (Figure 6), which has an experimental frequency of 308 Hz. are presented on Table 6 for the three models.

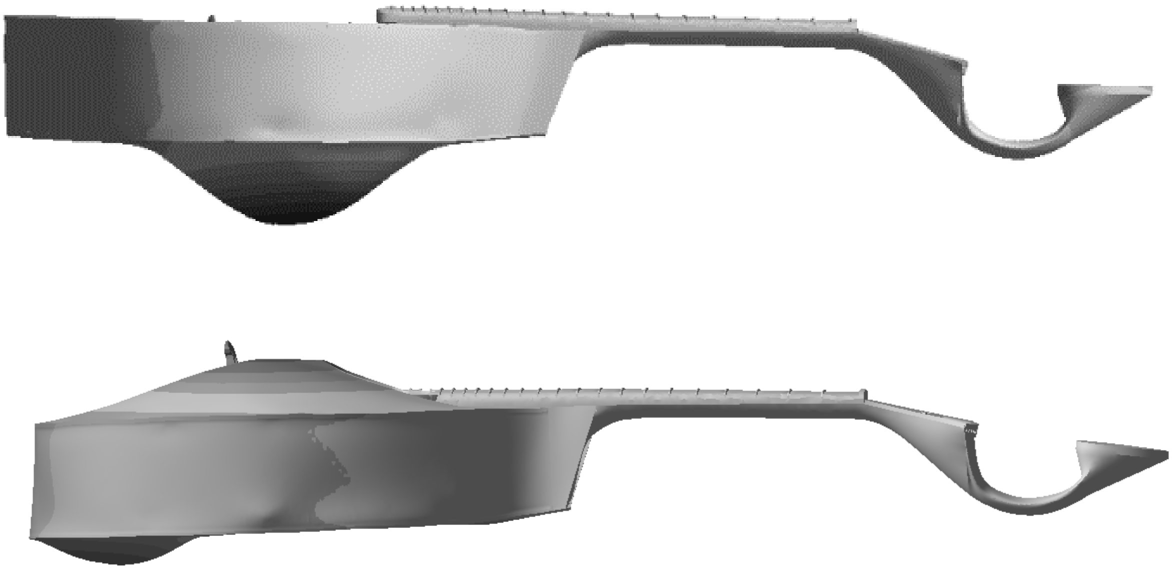

Figure 6 – Generic representation of the fourth coupled mode shape.

Table 6 – Numerical frequencies for the fourth coupled mode.

	Model 1	Model 2	Model 3
Frequency (Hz)	283	285	283

An antisymmetric B(1.1) mode is denoted on the fourth coupled mode. Such mode is very rare on classical guitars [11]. [12]. but appears on all the tested models, thus being common on Portuguese guitars. as it has been identified on previous experimental modal evaluations. It appears that the size of the soundhole does not affect this mode in any specific way.

4 Conclusions

Three different coupled models were built and tested on a FEM software. in order to evaluate the influence of the soundhole diameter on the dynamic modal behavior of the Portuguese Guitar.
The obtained results indicate that, for the first identified coupled mode. the soundhole dimension has little influence. Still, the smaller soundhole registered a difference from 89 Hz to 83 Hz. almost 7%. The second coupled mode, usually referred as the Helmholtz resonance mode, seemed to be the most dependent on the soundhole size. with numeric frequencies varying from 164 Hz (from the bigger soundhole) to 135 Hz (on the smaller soundhole). This was most expected. since the Helmholtz mode is very dependent on the size of the resonant chamber. The third mode is not much affected in a way that the frequencies shift from 311 Hz on the bigger soundhole to 306 Hz on the smaller soundhole. Finally, the fourth mode, appeared not to be, in any way. affected by the soundhole size. Although other results should confirm this. it may be more dependent on the geometric parameters of internal reinforcements of the chamber (the ribs) and on the general shape of this chamber.
A generic conclusion can be drawn from these results: apparently, smaller soundholes create lower pitch guitars. whilst bigger soundholes promote general higher frequencies obtained from the instrument.
The presented results constitute the preliminary conclusions from a broader research on the evaluation of geometric parameters on the dynamic behavior of the Portuguese Guitar. Still, the conclusions drawn so far are already useful since they uncover, for the first time. the numerical results for the influence of the soundhole size for this specific instrument. This information is of tremendous use for luthiers. as empirical knowledge may now be compared to this computational data.
Further research is strongly suggested for the numerical modes found for higher frequencies and for different geometrical parameters.

References

[1] O. Inácio. F. Santiago and P. Caldeira Cabral."The Portuguese Guitar Acoustics: Part 1 – Vibroacoustic Measurements". Proceedings of the IV Iberoamerican Acoustics Congress. 2004.

[2] E. Costa. P. Serrão. A. M. R. Ribeiro and V. Infante. "Dynamic Analysis of Portuguese guitar Strings". 15th International Conference on Experimental Mechanics. 2012.

[3] V. Debut. M. Carvalho. M. Marques and J. Antunes. "Three-dimensional time-domain simulations of the string/soundboard coupled dynamics for a twelve-string Portuguese guitar". CFA Poitiers. 2014.

[4] J. Meyer. "Fundamental resonance tuning of guitar". Journal of Guitar Acoustics. 1982.

[5] I. M. Firth. "Physics of the guitar at the Helmholtz and top plate resonances".J. Acoustical Society of America. 61 (2). 588-593. 1977.

[6] R. Vaz. "Modelo de elementos finitos da guitarra portuguesa". Unpublished work. 2012.

[7] G. Paiva. "Análise modal vibroacústica da caixa de ressonância de uma viola caipira". 2013.

[8] Elejabarrieta. M. J.. Ezcurra and A.. Santamaría.. "Coupled modes of resonance box of the guitar". J. Acoust. Soc. Am.. Vol. 111. No. 5. pp. 2283-2292. 2002.

[9] Vieira. M.. Serrão. P.. Infante. V.. Ribeiro. A. M. R. *Structural Modelling and Experimental-Numerical correlation of the Dynamic Behaviour of the Portuguese Guitar by Using a Structural Fluid Coupled Model*. WESPAC – Western Pacific Acoustic Conference. December 2015

[10] E. Hurtado. J. Ortega. J. Arreguin. A. Olmedo and J. Meneses "Vibration analysis in the design and construction of an acoustic guitar". International Journal of Physical Sciences Vol. 7(13). pp. 1986 - 1997. 2012.

[11] T. Gore. "Wood for Guitars". Proceedings of Meetings on Acoustics. 161th Meeting. 2011.

[12] H. Wright. "The acoustics and psychoacoustics of the guitar". Doctor of Philosophy Thesis. University of Wales. 1996.

[13] D. Green. J. Winandy. and D. Kretschmann "Wood Handbook - Mechanical Properties of Wood". Chapter 4. 2010.

[14] A. Ezcurra. M. J. Elejabarrieta and C. Santamaria. "Fluid–structure coupling in the guitar box: numerical and experimental comparative study". Applied Acoustics 66 (2005) 411–425. 2004.

[15] S. Probert. "Design. Manufacture and Analysis of a Carbon Fiber Epoxy Composite Acoustic Guitar". University of Washington. 2007.

[16] K. Marshall. "Modal analysis of a violin". J. Acoustical Society of America. 77 (2). 695-709. 1985.

[17] O. Inácio. R. Ribeiro. "Research Activity Report: Dynamical Analysis And Improvements On The Portuguese Guitar Strings And String-Body Interaction". 2012.