EXPERIMENTAL MODAL ANALYSIS OF A FULLY ASSEMBLED PORTUGUESE GUITAR

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Abstract
The most distinctive Portuguese traditional music style is Fado. In this form of Portuguese music a singer is accompanied by two instruments: a classical guitar and a pear shaped plucked chordophone with six courses of double strings – the Portuguese guitar. There are two distinct types of this instrument – the Lisbon and the Coimbra models – named after the towns where the two different styles of Fado have developed. These guitars differ basically on their size and tuning, both comprising 6 orders of double steel strings, while the construction method (strutting patterns, wood species used and soundboard thickness distribution) vary for different builders.
As part of a research project that addressed the vibroacoustical behavior of this instrument an experimental modal analysis of a fully assembled Coimbra guitar was performed. In this work we present the results of this analysis showing the main characteristics of the frequency response and significant vibratory modes.

Keywords: Portuguese guitar, modal analysis, vibratory modes.

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1 Introduction

This paper sums up the milestones and outputs reached during the work developed at the Musical Acoustics Laboratory of the Escola Superior de Música e das Artes do Espectáculo do Instituto Politécnico do Porto, for the modal identification of the Portuguese guitar body. This research work was part of a broaden research project which aimed at evaluating the physical properties of the strings and determine its influence on the guitar sound and playability.
It is well understood that besides the string intrinsic parameters and characteristics it is of utmost importance understanding the dynamical behavior of the guitar's body and string-body interaction. Hence, the modal identification of the guitar bodies is of interest.
In addition, the mechanics of the vibrating string is influenced by the bridge movement which transmits its vibration to the soundboard, acting as a damping mechanism as seen by the string. Hence, frequency response functions of the guitar were also measured at the bridge to determine local and transfer characteristics along the different coupled string points. The work was then focused on two main tasks:
1 – Modal identification of the guitar bodies: determining the modal shapes and parameters for a fully assembled Coimbra Guitar;

2 – Determination of the dynamical forces at the instrument bridge by measuring the frequency response functions for the interaction between bridge and sound board of a Coimbra's Guitar.
In the following sections a brief overview of the work undertaken is presented. The methodology is described, including the dimensional and general characteristics of the tested guitar and measurement equipment, set up and point mesh - excitation and receiver locations. The main results are presented divided into two separate sections: full body modal analysis and bridge/soundboard coupling. In the final section the most relevant results and conclusions are discussed.

2 The Portuguese Guitar

The Portuguese guitar is a pear-shaped plucked chordophone, with six courses of double strings. It has a characteristic sonority clearly associated with *fado* [1] and it has been extensively studied from an ethnological and musicological perspective (see [2] and [3]). The first scientific studies of the vibroacoustic dynamics are very recent [4]. A subjective acoustical quality evaluation was also performed where listening tests were made by a set of 60 individuals, all of which had an academic or professional relation with music. From it, it is suggested that *timbre* is the most relevant parameter [5]. Since then, several other studies have been performed around the Portuguese Guitar subject, from the analysis and simulation of the behavior of worn strings (see [6] and [7]), structural modelling of the body (see [8]) to time-domain modelling of the complex coupling between the twelve strings and the body of the instrument (see [9], [10] and [11]).
This unique instrument has its origins from the Renaissance European *cittern*. During the last century the main technical modifications (dimensions, mechanical tuning system, among others) took place [1]. Nowadays, the Portuguese guitar has become fashionable for solo music as well as for accompaniment, and its wide repertoire is often presented in concert halls and at classical and world music festivals around the world [2].
Usually, only two models of the Portuguese Guitar are considered: Coimbra and Lisbon guitar. Nevertheless a third can also be found, again with slightly different characteristics and known as Porto guitars [4]. Each of the previous types differ mainly in their sizes and tunings. Lisbon guitars have an effective length of 440-445mm while Coimbra and Porto guitars the length is usually 470mm [12].
Besides its pear-shaped format, the top plate (soundboard) is usually slightly curved and the back plate can be also curved or flat. Top and back plate are joined by the sides. The sound hole on the top plate is round and typically decorated with pearl-shell infills. The six courses of double strings (lowest three double to the octave and the remaining three higher-pitched order are two unison strings) are stretched from the nut to the *atadilho* passing over the bridge [2]. Figure 1 shows some examples of this instrument.

Figure 1 – Portuguese guitars: a) Lisbon, b) Coimbra and c) Porto models.

3 Experimental Procedure

3.1 Methodology

A full experimental modal analysis, based on impact testing was performed on a fully assembled Coimbra guitar. To determine the relevant modal characteristics, frequency response functions were measured using an impact excitation and small accelerometers. The impact points were distributed along the instrument, at the soundboard, back plate, sides and fingerboard components in a 2cm x 2cm point mesh. All impacts were perpendicular to its components.
For all impact positions three light weighted accelerometers, positioned at each main component (soundboard, back plate and sides) measured the acceleration response.
Trigger and measurement set up conditions (ex: excluding double hits) were pre-defined to ensure measurement quality. Two impacts were considered for averaging each hitting point.
To determine the dynamical forces at the instrument bridge another measurement set up was considered. The frequency response functions were measured to analyse the interaction between bridge and soundboard of the Coimbra guitar. Eight impact positions were considered (six vertical and 2 horizontal). For all impact positions one tri-axial light weighted accelerometer was placed, at six different positions - one right beneath each double string group. This set up allowed the determination of point and transfer accelerances.
Once again, trigger and measurement set up conditions (ex: excluding double hits) were pre-defined to ensure measurement quality. Three impacts were considered for averaging each hitting point.
The instrument characteristics, measurement set up and point mesh (excitation and measurement locations) are detailed in the following sections.

3.2 The tested instrument

The tested instrument was a Portuguese guitar Coimbra's model with six courses of double strings. It was a commercial model previously used to play in *Tunas* and *Fado* events. No information concerning to the builder or material was available.
A full 3D digital scan of the guitar was made and an output "*.iges" file was created.
The soundboard (top plate) and back plate are both slightly curved. The soundboard thickness is 3mm. The main instrument dimensions are as follows:

Table 1 – Tested instrument dimensions

Component	**Width [mm]**	**Length [mm]**	**Height [mm]**
Top Plate	375 (Max)	387 (Max)	3
Sides			7,5 (near the neck) 8,1 (mid soundboard) 8,0 (near *atadilho*)
Back Plate	375 (Max)	400 (Max)	*

* The soundboard thickness is 3mm. The back plate thickness was impossible to determine, but was assumed to be also 3mm when determining the sides dimensions.

The bridge is at 145mm away from the *atadilho* (a small tailpiece at the end of the body of the instrument) and centred on the top plate. The effective string length is 473mm.
The guitar strings are set at a variable height along the bridge. Starting from the higher pitch double steel strings the heights referred to the top plate are: 16 / 19 / 20 / 20 / 19 / 16 mm.
The strings were properly tuned and dampened by resilient rubber or mineral wool pieces. The total length of the instrument is 846mm.

3.3 Measurement equipment

To acquire the frequency response functions the following equipment was used:

Table 2 – Measurement instrumentation and hardware

Equipment	Brand	Model	Serial Number	Sensitivity
Instrumented Impulse Hammer	Mmeggitt Endevco	2302 – 10	2983	2.250 mmV/ N
Accelerometer	B&K	Deltatron type 4507B	30061	9.952 mmV/ms^{-2}
Accelerometer	B&K	Deltatron type 4507B	30062	9.170mmV/ms^{-2}
Accelerometer	B&K	Deltatron type 4508	10379	10.130 mmV/ms^{-2}
Triaxial Accelerometer	Dytran	3023A	4464	X – 10.4 mmV/g Y – 10.7 mmV/g Z – 10.7 mmV/g
Data aquisition. harware	Siglab	20-42	11770	-

3.4 Measurement set-up

The measurement sessions occurred throughout different dates. The Guitar was hanged on elastic cables, supported on a rigid structure (metallic beams) connected to the walls.
For the full body modal analysis, a point mesh of 2 cm x 2 cm was defined for each component. Given the instrument shape and dimensions the point mesh was centred along the fingerboard axis.
For the sake of simplicity each component was given a measurement point range, as follows:

Table 3 – Measurement point range

Component	Point Range	Total number of measurement points
Fingerboard	900 – 999	From 900 to 947 = 048
Top Plate	600 – 899	From 601 to 829 = 229
Sides	300 – 599	From 332 to 418 = 074
Back Plate	000 – 299	From 001 to 254 = 254
	TOTAL	**605**

All measurement points were identified according to the defined orthogonal axis:

XX: positive direction from higher to low frequency strings;
YY: positive direction from the bridge to fingerboard;
ZZ: positive direction from back to top board

Three accelerometers were used simultaneously during each impact testing

Table 4 – Tested instrument dimensions

Accelerometer	Siglab Ch	Component	Point
SN 30061	Ch02	Top Plate	740
SN 30062	Ch03	Sides	356
SN 10379	Ch04	Back Plate	073

For the defined measurement meshes, impact tests were made. Each frequency response function was obtained after averaging 2 samples. The different impact directions are exemplified in Figure 2.

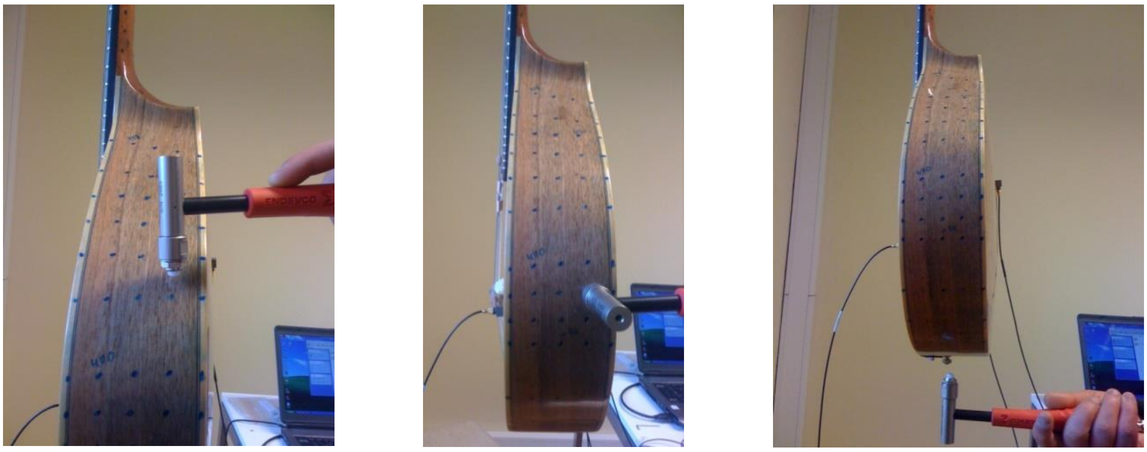

Figure 2 – Excitation at the sides at different directions and the 3 measurement position

For the bridge and soundboard coupling, a different set of measurements were made. The guitar was supported horizontally and six accelerometer (triaxial) positions were considered (right beneath the each string couple) while eight impact positions were considered (six vertically and 2 horizontal).

Figure 3 – Excitation at the bridge in different directions

4 Results

4.1 Full body analysis

A typical accelerance frequency response function for the three reference DOF is shown in the next figure (TOP: soundboard / MIDDLE: sides / BOTTOM: back plate). The impact was at point 720 (at sound board side, aligned with the instrument bridge at the high frequency strings end).
Interestingly to note that up to nearly 600 Hz both soundboard and back plate show similar magnitudes at the resonances frequencies. On the other hand, the sides start to show higher magnitudes of vibration above 700 Hz.
Even though there was no accelerometer on the finger board is interesting to compare in Figure 5 the accelerance frequency response function at two different impact locations point 720 (in blue and similar to previously stated) and point 935 (finger board near the nut). A strong coupling is only found at 88Hz.
Once the data was collected the modal identification was made using STAR6 System™ Modal Analysis Software using a multi-reference parameter estimation and software routines. The modal identification was vast and only a selected number of mode shapes will be shown in this paper. Modal frequencies were identified starting at 88 Hz with a mode shape associated with a beam flexural mode of the whole instrument without significant contribution to the radiated sound as confirmed by a microphone located in front of the instrument. However, the main air cavity mode, responsible a major

part of the low frequency radiation of the instrument was found at 125 Hz (see Figure 1). In this case a strong coupling with the soundboard vibration was detected.

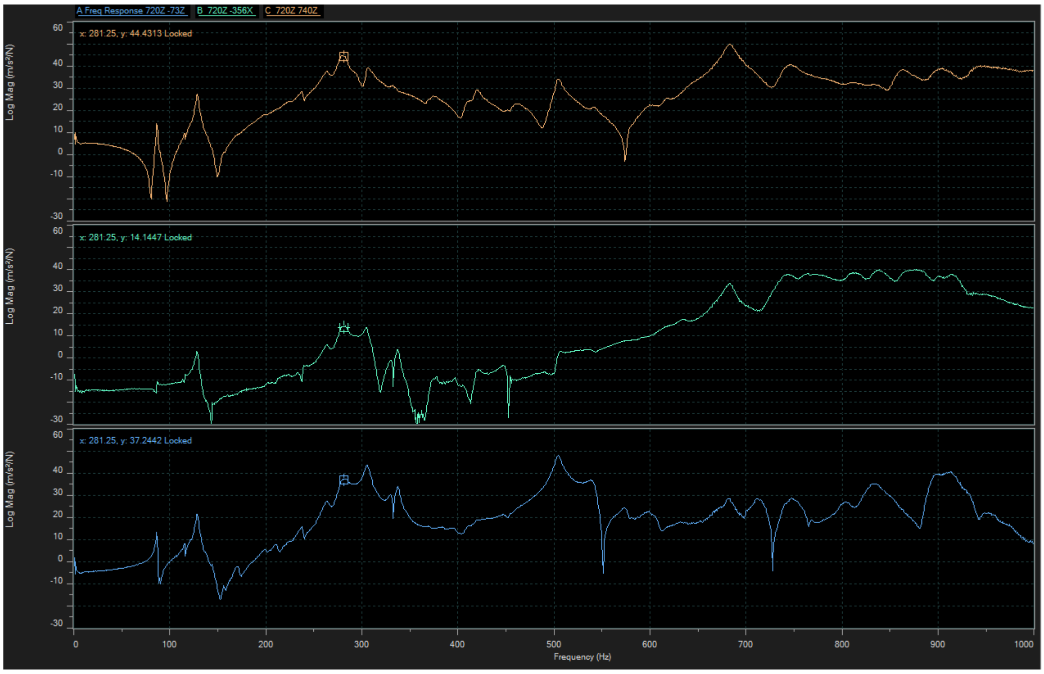

Figure 4 – 3 FRF’s at each measurement point: excitation at point 720 (Soundboard)

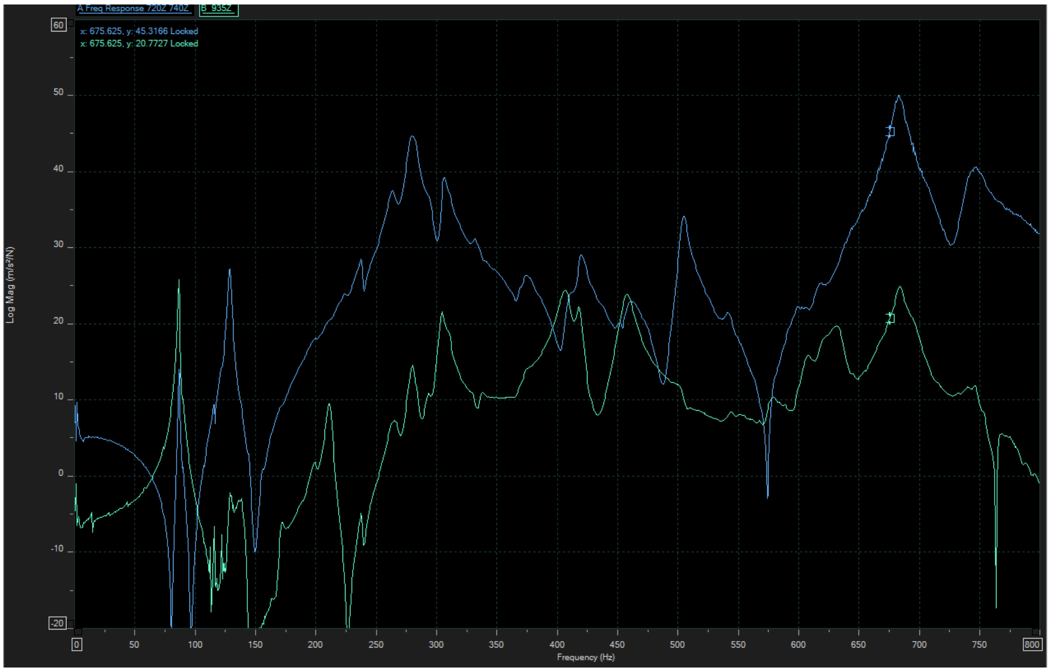

Figure 5 – 2 FRF at the soundboard measurement point: excitation at point 720 (Soundboard) and 935 (fingerboard)

Between the 200 and 600 Hz major resonances or groups of resonances were found, with relevant contribution to the radiated spectrum. The next figures illustrate some of the mode shapes.

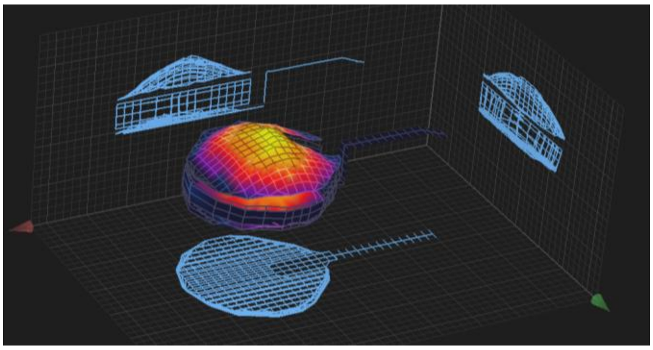
Figure 6 – Mode at 125 Hz with strong coupling with the air cavity mode

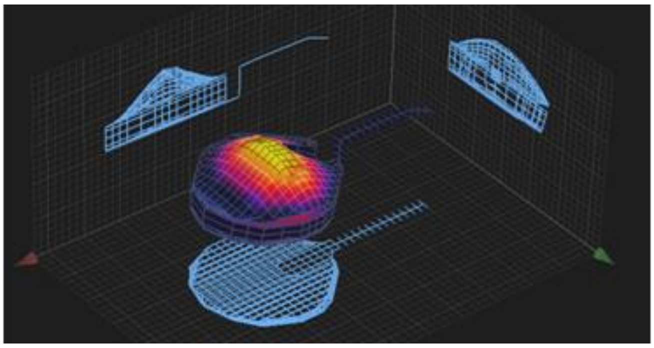
Figure 7 – Mode at 280 Hz without coupling to the air cavity mode

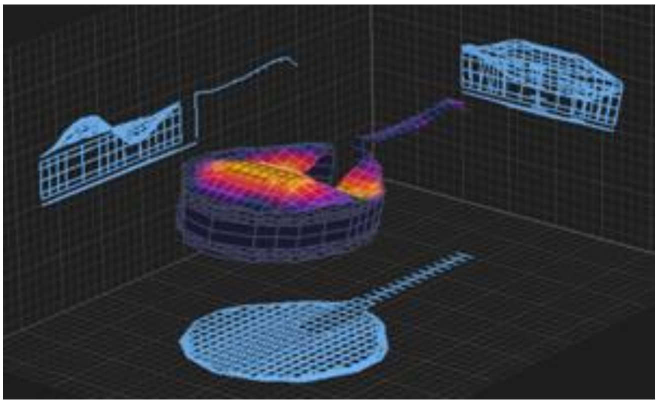
Figure 8 – Mode at 406 Hz showing the dipole behaviour of the soundboard

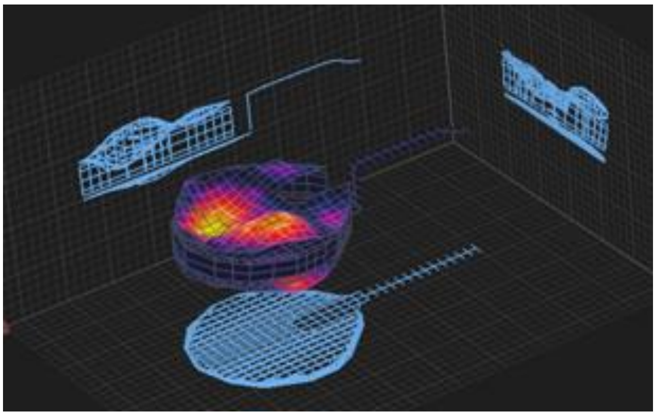
Figure 9 – Mode at 684 Hz showing the quadropole behaviour of the soundboard

4.2 Bridge and soundboard

As described before, measurements were made to determine the transfer function between excitation at the string location on the bridge and response at the soundboard immediately close to bridge. As an example Figure 10 shows the accelerance frequency response function with vertical impact at the 6 strings location on the bridge and response beneath the 4th double string on the soundboard. Figure 11 shows the result of an horizontal impact on the bridge longitudinal direction (+Y and –Y) and response also beneath the 4th double string on the soundboard.

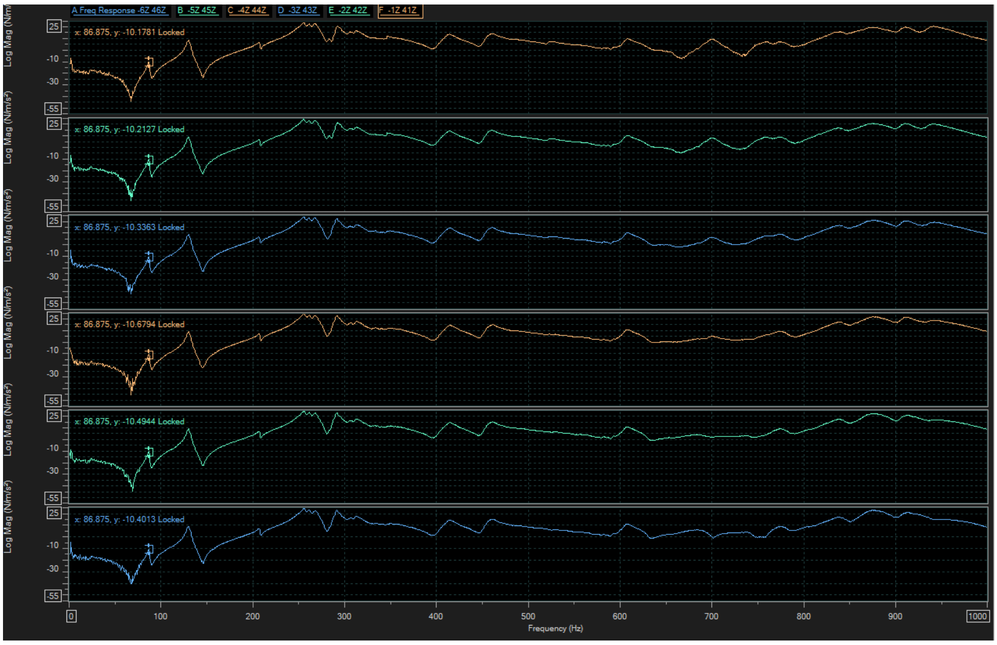

Figure 10 – FRF for 6 excitation points on the bridge and accelerometer beneath the 4th string

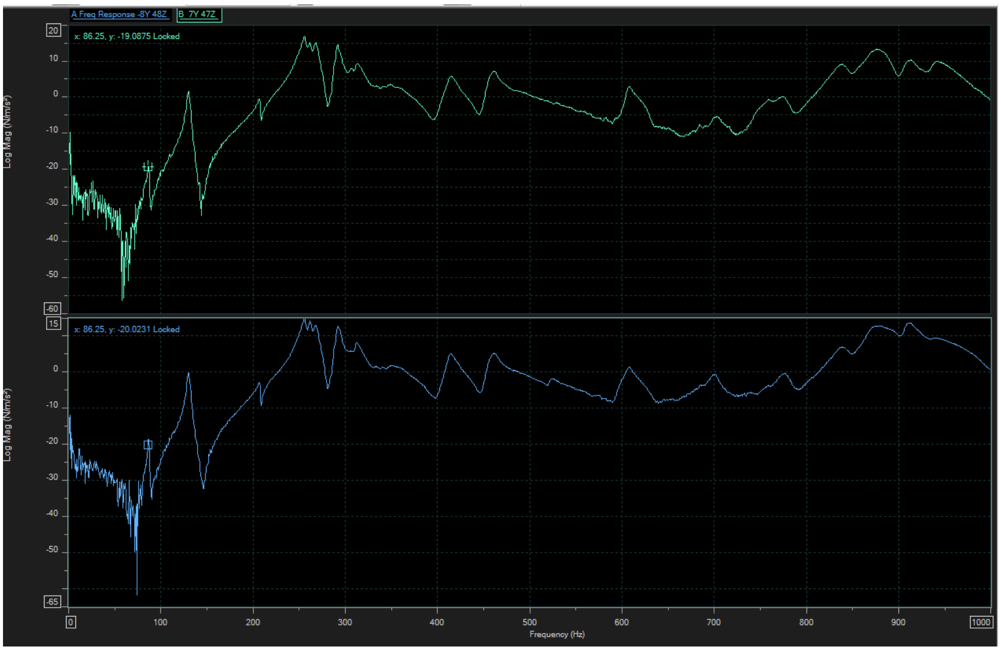

Figure 11 – FRF for 2 excitation points on the bridge (Y direction) and accelerometer beneath the 4th double string

5 Discussion

Below 200Hz two peaks were clearly identified and are according the published previous studies [4]. The first one at 88Hz, proved to be due to the coupled motion between the fingerboard and the body, which is also found in classical guitars [13].
At the frequency of 125 Hz a second mode was identified. According to the previous studies, the second peak is a mode with a high radiation efficiency and related to the air cavity mode that occurs inside the body of most string instruments with a hollow resonator [14]. The previous results show a mode where the soundboard and the back plate are strongly coupled and the sides and fingerboard have minimal displacements.
Between 250 Hz and 800 Hz many resonances were found. The most important is the (0,0) monopole mode found at 280 Hz, given its high radiation efficiency. Interesting to note is that between 300 and 500 Hz (0,1) longitudinal dipole modes where found. The first two, at 308Hz and 338 Hz show higher displacements at the back plate compared to the soundboard. On the other hand, the remaining two at 406 Hz and 458 Hz show higher displacements at the soundboard compared to the back plate. Interestingly at 406Hz it seems that the soundboard as a mode completely independent from the remaining body.
Above 500 Hz, at 505 Hz a first axial mode (1,0) was found. However, at 575Hz the soundboard once again shows a longitudinal behavior but this time a tripole mode in both sound board and back board, with the latter showing higher displacements. This behavior is also found at the frequency of 604 Hz.
The quadropole mode shapes only shows up at the frequency of 684 Hz for the sound board. However, at this frequency the back board shows a longitudinal dipole mode shape. At 697Hz both soundboard and back board show a quadruple mode shape. Above 700 Hz other higher order modes were observed.
For the bridge analysis similar frequency response functions ere obtained, for the “z” and “y” impact points and often correlated with the resonance modes identified during full body analysis. Only the first three coupled string groups show a resonance mode around 500 Hz.

6 Conclusions

In this work we focused on the modal identification of the guitar bodies: determining the modal shapes and parameters for a fully assembled Coimbra Guitar. In addition, the dynamical forces at the instrument bridge were also determined by measuring the frequency response functions for the interaction between bridge and sound board of a Coimbra’s Guitar.
The measurement procedure and set up were presented. The main results were presented and were aligned with previous investigation. An acoustically inefficient structural mode was identified at the 88 Hz whereas the cavity mode was identified at 125 Hz. Above this frequency it was also possible to identify several other mode shapes for both the sound and back board. The monopole mode was identified at the frequency of 280 Hz. The mode shapes for the sound board and back board not always correspond to the same frequency.
For the bridge analysis, similar frequency response functions were found suggesting correlation with the resonance modes identified during full body analysis.
The full body modal analysis and bridge to sound board measured frequency response functions were inputs for other subtask of the research project and further studies.

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