

Preservation and Study of Historical Guitars

Museu de la Musica, Catalunya :

Methodology Proposal to Play the Unplayable

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Master's thesis

Abstract

WoodMusick project is a multi-disciplinary COST action research project. The main goal of the project is to study museum instruments and preserve their physical and acoustical properties. This paper aims to contribute the project by studying historical guitars in Museu de la Musica, Catalunya, as well as to propose a global measurement methodology for prediction of acoustical properties of guitars during the design stage. Two historical classical guitars, Torres 625 from Antonio de Torres and Labrador from romantic period are studied, in addition to a test guitar. Steady-state and impulse responses are recorded and spectral and physical properties are extracted from recordings. The results are classified with WEKA by ESSENTIA descriptors and two guitars are successfully identified and distinguished from each other. Extracted features and physical properties are observed in the latter stage and sound feature estimations are proposed. Besides the multi disciplinary nature of the study is already a challenging task, the main obstacle turned out to be to build a methodology that ensures safety of the instrument while collecting the necessary data. The results are promising for building a dataset with proposed methodology to predict acoustical features of guitars in design stage as well as creating an archive for historical instruments and monitor their physical state and its effect on sound features in time.

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Chapter 1

Introduction

1.1 Motivation

Research in the field of musical acoustics is of great importance for large variety of branches, instrument making, ecology and eco-acoustics, acoustics and physics, sound engineering and music technology since years for different reasons. Finding new sound-board materials for eco-acousticians as well as predicting the sound quality of the instrument for luthiers, understanding lip pressure of wind instruments for physicians and acoustical radiation patterns of instruments for acousticians are some of the pre dominant research areas of these branches, as well as many others.

“WoodMusick” aims to preserve and study historical wood instruments which are part of different museums and collections all around Europe. The diversity of parties that are part of the project corresponds to the multi-disciplinary nature of the study. This paper, however, focuses on the study of sound, particularly for the historically important classical guitars which are the part of the rich collection of Museu De La Musica in Barcelona, Catalunya.

Guitars as well as the other members of the string instruments’ family are particularly challenging and tempting for researchers especially because of its inharmonic nature and complex vibrational behavior. The major difference between guitar and its well-known family members, violin, cello and piano, is that there is considerably less amount of resources and papers (not as less as there is for *lute* and *vihuela*, considered as ancestors of guitar) in the state of the art, simply because guitar has been accepted by major orchestras around 1800-1850, and world-wide in the second half of 19th Century, by the help of legendary musicians like Francesco Tarrega. Even though the history of guitars and string instruments is beyond the scope of this paper, a slight introduction is presented at the beginning of the second chapter.

1.2 Goals

This study aims to create a substantial ground to build a scientific relation between structural and physical aspects and acoustical properties of guitar in the first scope. This will improve the chances of creating a suitable acoustical property model which can help predicting sound aspects of guitars from the early stage of guitar construction. The research and methodology applied in order to achieve this goal is as follows:

- Examining the state of the art review, focusing from physics of musical instruments to audio measurement techniques as well as acoustical properties of wood material that has been used for making string instruments.
- Physical and acoustical measurements of the data set.

- Feature extraction of the captured audio samples and observation of frequency response functions.
- Investigation of physical dimensions and their effect on the extracted results.
- Acoustical property model proposal and testing its reliability for bigger datasets.

1.3 Structure of the thesis

In chapter 2, the physics of string instruments, mostly focused on guitar, and acoustical properties of wood is reviewed. Furthermore, different measurement techniques, string and plate resonances, and high quality sound criterion is examined. Chapter three introduces the methodology covering from measurements to the sound prediction model proposal. Chapter four focuses on the results obtained by feature extraction. All the results and corresponding measurements are presented in a table. Chapter five discusses the sound prediction model proposal under the light of the results reviewed in the chapter four as well as an overview as a summary, stating the contribution to the state of the art.

Chapter 2

State of the Art

This section reviews the concept and relative research work in the physical and acoustical analysis of musical wood string instruments, emphasizing on guitar, with an overview of history, and acoustic and vibro-acoustic measurement methods. The first subsection briefly describes physical aspects of wood string instruments, from both constructional and acoustical point of view, mainly focusing on the working principles and structural development of guitars including overview of acoustic properties of wood and influence of guitar design on sound quality.

2.1 String instruments

Quite a number of resources are available about histories of acoustics in research domain (Lindsay 1966, 1973; Hunt 1992; Beyer 1999), and these histories include musical acoustics as well. Carleen Hutchins has written about history of violin research (Hutchins, 2000), but less has been documented regarding other string instruments.

Most early acoustical studies were tied to musical acoustics (Rossing, 2010), beginning from Pythagoras studying length of the strings and vibrations as well as Galileo reviewing the relationship of pitch of a string to its vibrating length (Hunt, 1992), and his accomplishment of revealing the relationship of the number of vibrations per unit time and the pitch. The English mathematician Brook Taylor provided a dynamical solution for the frequency of a vibrating string based on the assumed curve for the shape of the string when vibrating in its fundamental mode. Daniel Bernoulli set up a partial differential equation for the vibrating string and obtained solutions which d'Alembert interpreted as waves traveling in both directions along the string (Beyer 1999).

History of guitars

There are basically two types of guitars: acoustic and electric guitars. Acoustic guitar family includes *flamenco* guitars, *Portuguese fado* guitars, *classical* guitars, *flat-top* guitars, *resonator* guitars, *archtop* guitars, *acoustic bass* guitars and *12-string* guitars.

Vihuela is the ancestor of modern six string guitar, which has its roots in antiquity. The modern word *guitar* was adopted in English from Spanish *guitarra*, which was derived from Greek *kithara*. In the renaissance period, the renaissance guitar, which was not a dominant instrument, had four courses of double strings, and towards the baroque period, fifth course was added. At the end of baroque period, the strings have been turned into single strings and an additional string was added, reaching its final state. Although some composers of eighteenth century, like Boccherini, included guitar into some of their chamber music, settlement of guitar as a concert

instrument took place largely in nineteenth century. Fernando Sor (1778–1839) was the first in a long line of Spanish virtuosos and composers for the guitar.

Substantial contribution was presented to the structure of guitars, by Spanish luthier Antonio de Torres (1817-1892), with the enlargement of body and introducing the fan shaped bracing to the top plate. Francesco Tarrega (1852–1909), on the other hand, one of the greatest players of nineteenth century, perhaps the best one, introduced the *apoyando* stroke, generally extended the expressive capabilities of modern classical guitar performance (Jahnel, 1981;Turnbull,1974).

Unlike its ancestors, *lute* and *vihuela*, which very little scientific research has been conducted, the guitar has been studied extensively, by multidisciplinary scientists. In addition to scientific papers, acoustic journals such as, *Acustical Acta Acustica*, *Applied Acoustics*, *Acoustics Technology and Journal of the Acoustical Society of America* have directed significant importance towards guitars. More specialized journals like, *Catgut Acoustical Journal*, *American Lutherie*, *Journal of Guitar Acoustics*, and *Frets* have also reserved space for research papers and investigations. Almost all of the international symposiums of musical acoustics (ISMA) included papers on acoustics of guitars, a special session of these papers were published in the September 1982 issue of *Journal of Guitar Acoustics*, a dedicated journal, not being issued after 1983.

Guitar researchers have paid considerable attention towards resonances of the guitar body, and how the low-frequency resonances can be acknowledged being due to the coupled vibrations of top plate, back plate and enclosed air (air cavity). Different bracing patterns, especially in the top plate, has been experimented by luthiers. Unlike the violin, which has changed very little since decades, guitar is still evolving.

2.2 Physics of guitar

This section reveals a brief overview on physics of guitar in two subsections consisting of plucked string motion, 1-D continuous systems, and 2-D continuous systems such as top plates and back plates of guitars. Strings are considered as *primary excitation mechanism* in physics as plates individually are referred *fundamental vibrating elements* and guitar body, mostly because of its coupling motion is considered as *resonator*.(Roederer, 2008)

2.2.1 Transverse waves of plucked strings

The study of vibrating string is along and developed field, beginning from Pythagoras observing how the division of a stretched string into two segments with the lengths of these two have a simple ratio (2:1, 3:1, 3:2, etc.) gives us pleasing sounds. It is an example of normal modes of a string fixed at its ends. Closer examination of this motion of a string reveals that normal modes are dependent on the length of the string, applied tension, mass of the string and the end conditions. The equation describing transverse wave motion in a vibrating string is (see e.g., Sect. 2.2 in Fletcher and Rossing 1999):

$$\frac{\partial^2 y}{\partial t^2} = \frac{T}{\mu} \frac{\partial^2 y}{\partial x^2} = c^2 \frac{\partial^2 y}{\partial x^2},$$

(2.1)

If a string with linear density m (kg/m) is stretched to a tension T , waves will propagate at a speed c given by $\sqrt{T/m}$. The general solution to (2.1) can be expressed in a form:

$$y = f_1(ct - x) + f_2(ct + x) \tag{2.2}$$

The function $f_1(ct - x)$ represents a wave traveling to the right with a velocity c ; similarly, $f_2(ct + x)$ corresponds to a wave traveling to the left with the same velocity. The nature of functions f_1 and f_2 are arbitrary, for example, they can be sinusoidal. (Fletcher & Rossing, 1999).

2.2.2 Impulsive waves, interference, reflection

In order to understand wave reflection at the ends of a string, we first need to consider what happens to a single pulse at fixed and free ends of a string (Rossing, 2002). If a rope is fixed in one end and given a sinusoidal force, a single impulse by rapidly moving the other end up and down, the impulse will travel in the speed of c while maintaining its shape towards the fixed end of the rope. When the impulse reached the end, it will reflect back from the end with an almost same shape except being upside-down. If the other end of the rope is not fixed, free to move, the impulse would travel back in the shape of right-side-up.

This motion of strings creates superposition and phase interference between traveling waves. When two waves are in motion at opposite directions, they can pass right through each other and emerge with their original identities, the principle of linear superposition describes this behavior (Fletcher & Rossing, 1999). When the pulses are in the same sense, they add when they meet, when they are in opposite senses, they subtract. These are called *constructive* and *destructive interferences*. (Fig. 2.1)

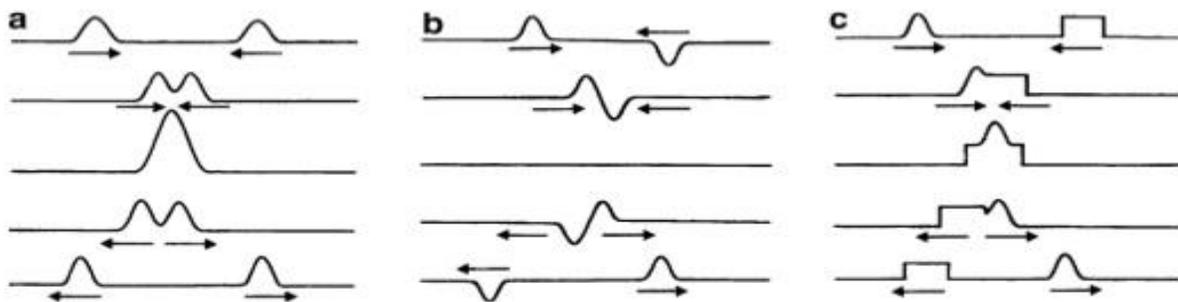


Figure 2.1: Superposition of Waves

The superposition of wave pulses that travel in opposite directions: (a) pulses in the same direction; (b) pulses in opposite directions; (c) pulses with different shapes

(Rossing, 2010)

2.2.3 Standing waves

When the both ends of the string are fixed, waves reflect back from the fixed ends and create *standing waves* (Fletcher & Rossing, 1999). The interaction of two waves, with equal amplitude and frequency, traveling in opposite directions, (fig.2.2 : green to the right, blue to the left, red one is the sum) there will be alternate regions of constructive and destructive interference. The figure 2.2 below, is a time sequence (time increases from bottom to top) representation of these alternate phase interferences, the points of destructive interferences occur are called **nodes**, and points of constructive interferences are called **antinodes**.

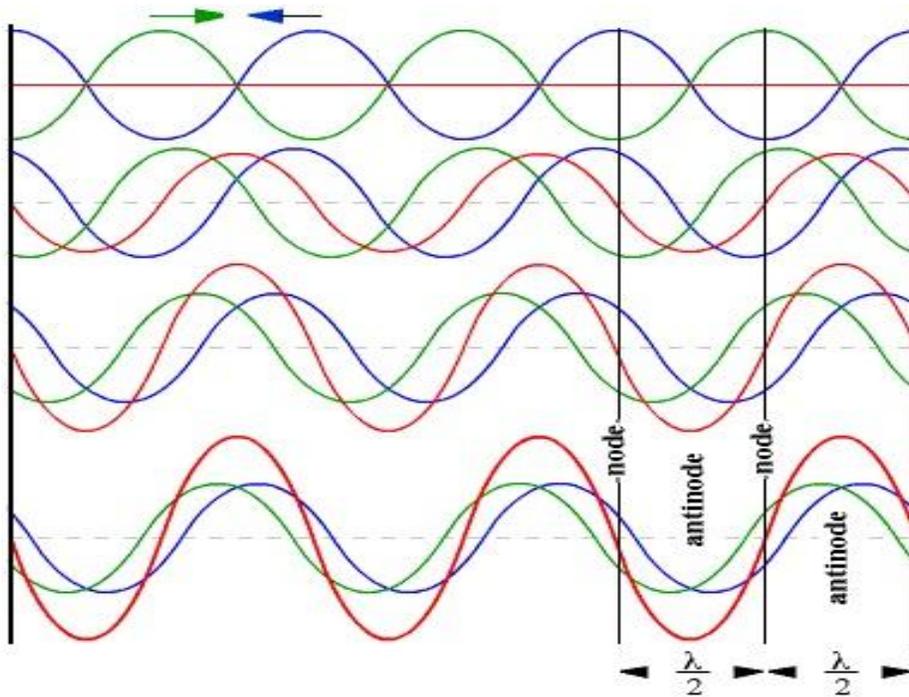


Figure 2.2: Nodes and antinodes of identical standing waves.

(<http://www.phys.unsw.edu.au/jw/strings.html>)

At the antinodes, the displacement oscillates in the same frequency of individual waves but the amplitude is equal to sum of their amplitudes. If the amplitudes of two waves are different, they will not cancel each other unlike it is shown in the figure 2.2, above. These nodes do not move on the string, as they are called *standing waves*.

2.2.4 Harmonics and modes

The string on a musical instrument is fixed in both ends, any vibration on string have nodes at both ends. When a string is plucked, the pulse waves propagate to the opposite directions and reflect back from the fixed ends, and create standing waves, as discussed above. The resulting vibration can be considered as a combination of vibrations at several modes. A string with a length L could have a standing wave of twice as long as the length of the string (wavelength of $2L$). This creates two nodes at both ends, and an antinode in the middle. This is one of the modes of a vibrating string. The relationship among the frequencies and these modes can be measured by, $f_n = v/\lambda_n$ where “n” is the number of harmonics “v” is the speed of the wave and “ λ ” is the wavelength. For example, if a string is plucked at its center, the result will be the fundamental frequency and the odd-harmonics.

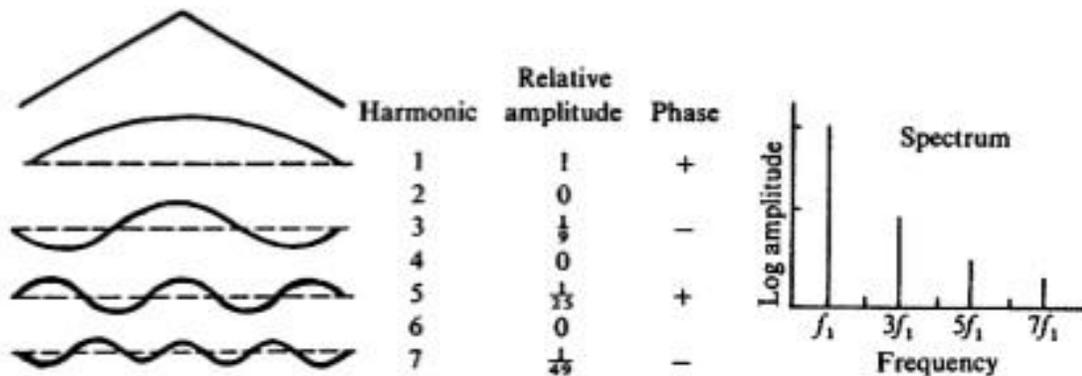


Figure 2.3 : Frequency Analysis of a plucked string at its center.

((Fletcher & Rossing, 1999a)

If the string is plucked any other position than its center, the spectrum of the modes is different (Rossing, 2010). Figure 2.4 shows the spectrum of a string plucked at one-fifth of its length.

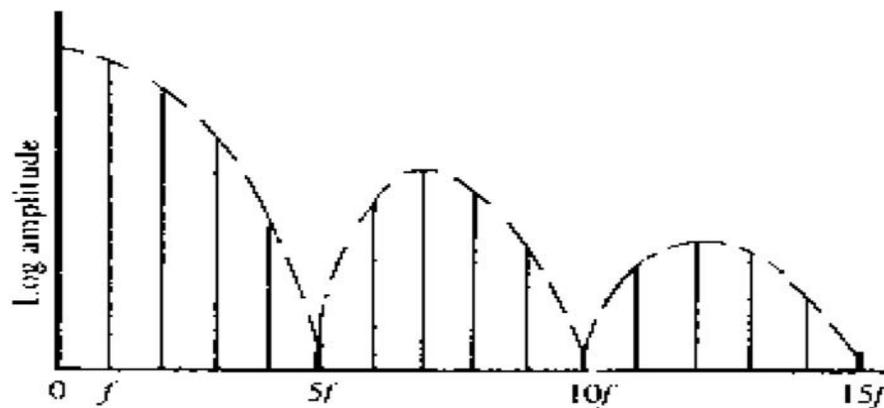


Figure 2.4: Spectrum of a string plucked one-fifth of its length.(Rossing, 2010)

The fifth-harmonic is missing in the fig 2.4. If the string is plucked at one-fourth of its length fourth harmonic will be suppressed and so on.

2.2.5 Force exerted by the string

For a first approximation, the force exerted by a plucked string can be written considering the force normal to the bridge is $T\sin\theta$, and parallel to the soundboard or plate is $T\cos\theta$, while T represents the tension and θ represents the angle between string and the plate. The tension changes during the cycle, as the length of the string changes, so if the string has a cross-sectional area A , elastic (Young's) modulus E , the transverse and longitudinal forces can be expressed as follows:

$$F_T = (T_0 + \Delta T)\sin\theta, \quad (2.3)$$

$$F_L = (T_0 + \Delta T)\cos\theta + \frac{EA\Delta L}{L_0} \quad (2.4)$$

The change in longitudinal force is due mainly to the slight change in length of the string during cycles. Transverse force change, on the other hand, is mainly because of the change in the direction or slope.

Amplitude of transverse force pulses, in a typical guitar pluck, is 40 times greater than the amplitude of longitudinal force pulses in the same motion, and they couple more efficiently to the top plate (Fletcher & Rossing, 1999). However, the longitudinal force pulses are proportional to square of the plucking amplitude, so the difference diminishes with the increasing amplitude. (Rossing, 2010; Fletcher & Rossing, 1999).

Plucking of guitars is examined under the physical modeling of strings subsection, towards the end of chapter 2.

2.3 Guitar body

The earliest known six-string guitar was built in 1779 by Gaetano Vinaccia in Italy (Rossing, 2010). The modern guitar generally has six strings tuned to E2, A2, D3, G3, B3, and E4 (82, 110, 147, 196, 247, and 330 Hz, respectively). The top is usually cut from spruce or redwood, planed to a thickness about 2.5 mm (Yoshikawa, 2007). The back is usually hardwood, such as mahogany, rosewood or maple, and again its thickness is generally 2.5 mm (Fletcher & Rossing, 1999b; Rossing, 2010). The choice of wood material is briefly examined at the fourth subsection of this chapter, however under the light of recent studies the well-known and generally accepted species are still recognized as decent and functional choices for guitar making (Brémaud, 2012; Pedgley, Norman, & Wood, 2014; Sedik, Hamdan, Jusoh, & Hasan, 2010; Timell, Wimmer, Roberts, & Aloni, n.d.; Yoshikawa, 2007).

Both the top and back plate are braced, and the bracing of the top plate is being one of the critical design parameters(Fletcher & Rossing, 1999b).

2.3.1 Coupled vibrators

The guitar body can be recognized as a system of a coupled vibrator, the plucked string radiate only small amount of sound directly, but acoustical radiation moves to top plate by the string exciting the bridge, and from top plate to the air cavity. As an overall result of this energy transfer process, efficient amount of sound radiates via the vibrating plates and the sound hole.

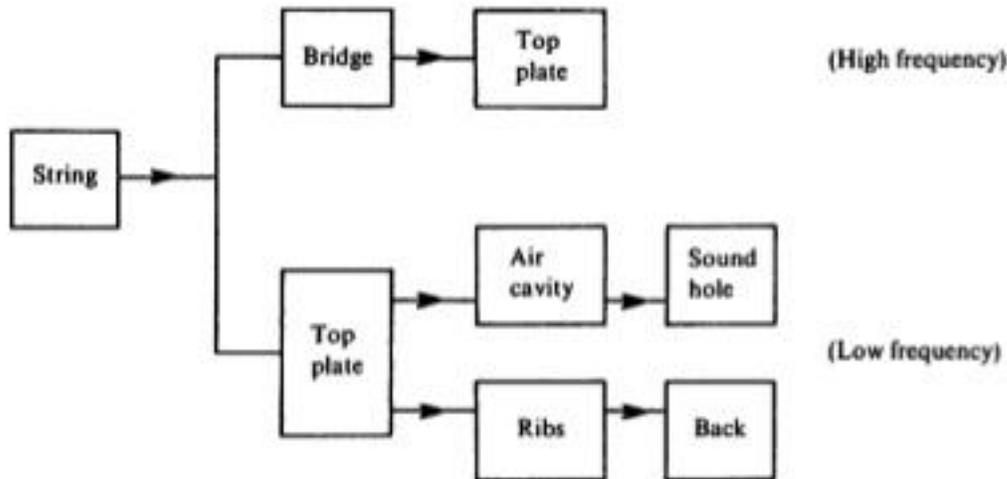


Figure 2.5 : Simple schematic of guitar.

(Fletcher & Rossing, 1999b)

Figure 2.5 summarizes the working principle of guitar. At low frequencies, top plate transfers the energy to the back plate via both air cavity and the ribs, the bridge functions as a part of the top plate, but at the high frequency range, top plate radiates most of the sound, the mechanical properties of bridge becomes significant.

2.3.2 Modes of vibration of guitar body

A guitar top plate vibrates in many modes. The mode shape and resulting frequencies change quite remarkably when the braces are added, in addition, they are totally different if the vibration measurement has taken place with guitar's edge free, clamped or simply supported.

Figure 2.6 shows the measured mode shapes and frequencies of a guitar plate without braces and with a free edge, and figure 2.7 presents the observed modes of a plate with traditional fan bracing. According to Richardson and Roberts (1985), the observed results are in good agreement (Fletcher & Rossing, 1999b). Various experiments have taken places to understand the effect of bracing systems towards the modes of vibration of top plates of guitars and violins, mostly with similar results(Boullosa, 2002; Elejabarrieta, Santamaría, & Ezcurra, 2002; Fletcher & Rossing, 1999b; Pizzigoni, 2010; Rossing, 2010; Torres & Boullosa, 2009).

The complex vibrations of guitar body, can be referred as normal modes of vibration, they are independent in ways which a structure vibrates (Rossing, 2010). They are characterized by the nodal lines (along the lines the vibration motion is minimum) and by antinodes, where the vibration motion is maximum. In the standing waves subsection of this chapter, nodes and antinodes are described briefly, regarding the explanation of these, now the medium is two-dimensional (guitar plate). The nodes create lines over the plates, and divide the plates into different sections. When a force is applied to any point on the structure that is not a nodal line, deflection of the structure creates modal shapes of particular frequency, called *operating deflection shape* (ODS) (Schwarz & Richardson, 1999). ODS may result from the excitation of more than one normal mode. When exciting a structure at a resonance frequency, the ODS will be determined mainly by one mode, although if several modes have nearly the same frequency, special techniques may be required to determine their contributions to the observed ODS. Modes of a structure are functions of the entire structure. A mode shape describes how every point on the structure moves when it is excited at a point. The distinction between a normal mode, an operating deflection shape, and a resonance is an important one to make in order to avoid misunderstanding (Richardson & Technology, 1997; Rossing, 2010).

Modal testing is a systematic method for identification of the modal parameters of a structure, such as natural frequencies, modal shapes, and modal damping. In guitar testing, the excitation is usually a sinusoidal force or an impulse. Detection methods include: measuring acceleration with an accelerometer; measuring surface velocity with a vibrometer; determining deflection by means of holographic interferometry; determining nodes with Chladni patterns. The measurement techniques will be investigated in the next subsection.

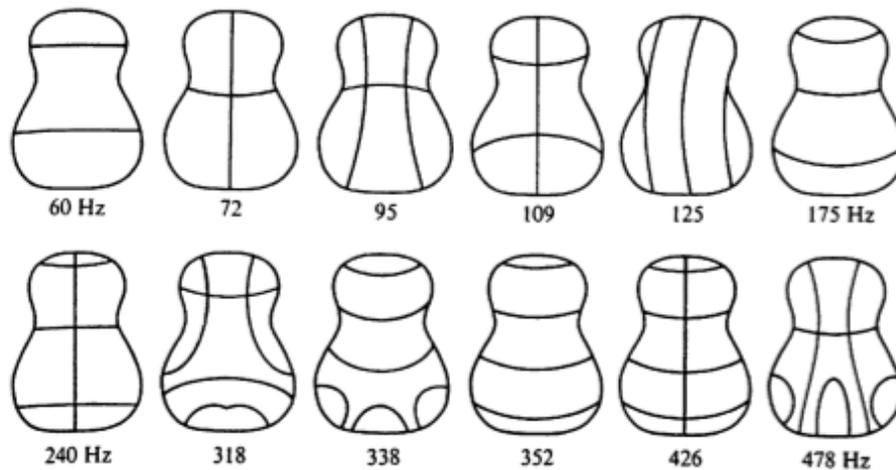


Figure 2.6 : Vibration modes of guitar without bracings.

(Richardson, Roberts , 1985)

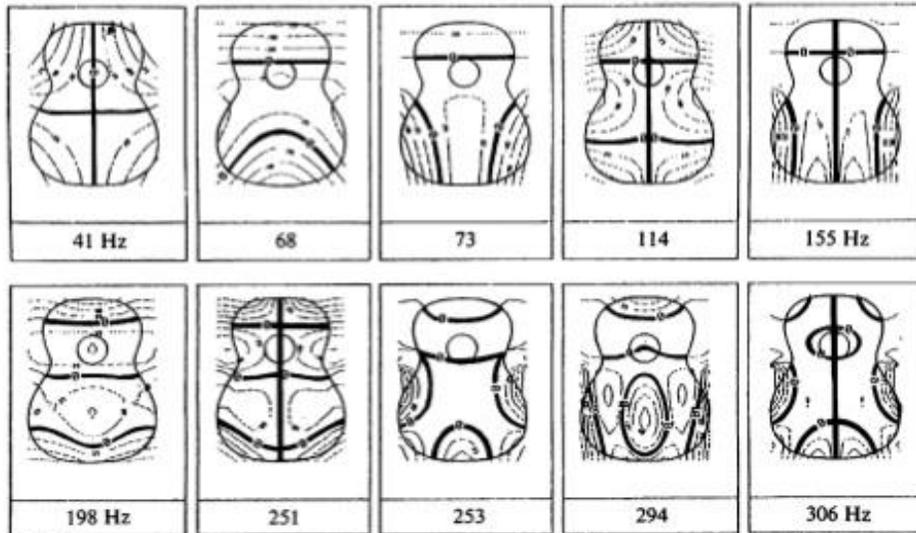


Figure 2.7 : Vibration modes of plates with bracings

(Richardson, Roberts , 1985)

2.3.3 Coupling between top plate and air cavity

The coupling of the vibrating components at low frequencies has been modeled by several investigators. If we fix the back plate and the ribs, the guitar can be viewed as a two-mass vibrating system as shown in figure. 2.8a. The vibrating strings apply a force $F(t)$ to the top plate, whose mass and stiffness are represented by m_p and K_p . A second piston of mass m_h represents the mass of air in the soundhole, and the volume V of enclosed air acts as the second spring. This model was proposed by (Caldersmith, 1995) and by (Christensen & Vistisen, 1980) and further developed by (Richardson and Roberts, 1985). The two-mass model predicts two resonances with an anti-resonance between them. These correspond to f_1 , f_2 , and f_A in figure 2.8b. The two resonances f_1 and f_2 span the lowest top plate mode f_p and the Helmholtz resonance f_A ; that is, f_A and f_p will lie between f_1 and f_2 . In fact, it can be shown that $f_1^2 + f_2^2 = f_A^2 + f_p^2$ (Ross and Rossing 1979; Ross 1979). If $f_p > f_A$ (as it is in most guitars), f_A will lie closer to f_1 than to f_2 , as shown in figure 2.8b.

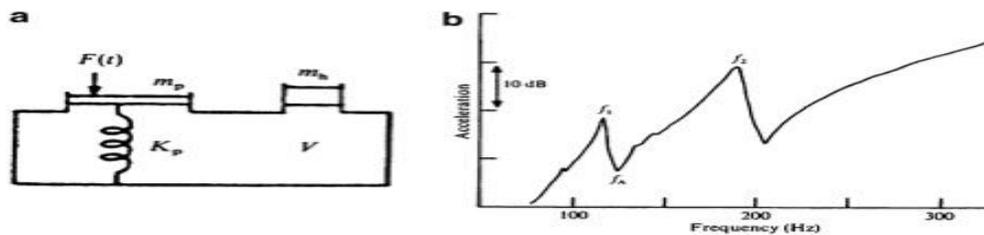


Figure 2.8 : Two-mass model
(Rossing, 2010)

Coupling of the back plate can be modeled as three-mass model, like in the figure. 2.9. An additional mass, m_b , an additional spring, K_b , is presented to represent the stiffness and mass of the back plate. Figure 2.9b shows three peaks and two dips (anti-resonances) in the spectrum graph. This model, proved to be true by several experiments carried out by (Rossing et al, 1985), states the relationship as: $f_1^2 + f_2^2 + f_3^2 = f_A^2 + f_p^2 + f_b^2$.

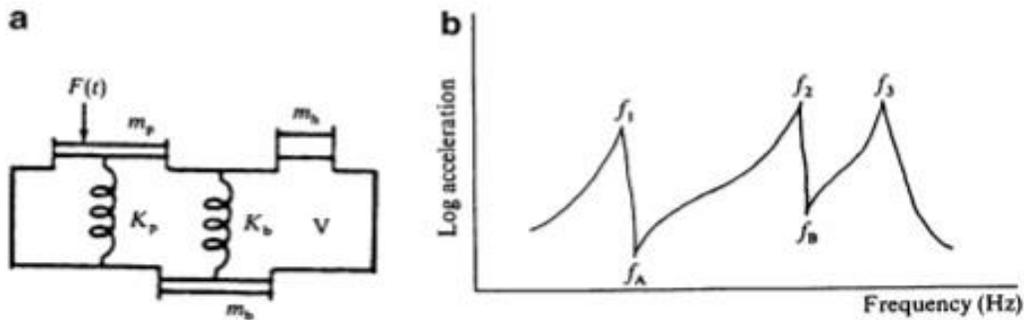


Figure 2.9 : Three-mass model.

(Rossing, 2010)

2.3.4 Low frequency resonances

The frequency response of guitar is characterized as series of resonances and anti-resonances. In order to determine the vibration configuration of major resonances, it can be driven sinusoidally at one or more points, and its motion can be observed, mechanically, electrically and optically. Optical sensing techniques include holographic interferometry (Stetson, 1981), laser velocimetry (Bulloasa, 1981) and acoustical detection techniques include scanning with a single microphone (Ross and Rossing, 1979) and using an array of microphones (Strong et al, 1982).

Most of the guitars have three resonance frequencies between 100-250 Hz. It is because of the coupling between back and (0,0) top modes and A_0 (Helmholtz) air mode (Rossing, 2010).

In the lowest frequency of resonance, top and back plate moves in opposite direction and makes the guitar move like it “breathes” in and out. With the second lowest resonance, both plates act accordingly, in the same direction. The highest resonance of the three, top and back plate once again moves in opposite direction but in this case air in the sound hole moves opposite the way it moves in the lowest resonance. It is observed by (Fletcher & Rossing, 1999b), measuring the resonant frequencies with free edge and with fixed ribs, only effect the second mode of resonance, as the center of mass moves. First and the third mode of resonances remain unchanged in frequency, because they involve very little motion of ribs. It can be assumed that because of the dependence of vibrational modes on the method of support, the timbre of the instrument depends on the way it is being held by the player.

Above 400 Hz, the effect of coupling is weaker, so the observed resonances are due mainly to resonances in one or the other one of the plates, usually top plate.

2.4 Sound quality

Most guitar players state that sustain and tonal strength is the most important single criterion for quality, following by timbre and tone length (Jansson, Vi, Vii, Function, & Tone, 2002). How the initial sound level and rate of decay in sound is examined in the previous section, stated these aspects are depended on resonances of guitar body. Jansson, 2002 and Rossing, 2010 states a questionnaire and its results of “sound quality” of guitars. Tones from recorded music were analyzed with long time average spectra (LTAS) and was found out that better guitars have higher level up to 3,000 Hz, and less good guitars tended to have lower level between 400 Hz – 2,000 Hz.

Extensive listening tests were conducted at the Physikalisch-Technische Bundesanstalt in Germany to try to correlate quality in guitars to their measured frequency response (Rossing, 2010; Meyer, 1983). Some of the features that correlated best with high quality were:

1. The peak level of the third resonance (around 400 Hz);
2. The average level of one-third-octave bands in the range 80–125 Hz;
3. The average level of one-third-octave bands in the range 250–400 Hz;
4. The average level of one-third-octave bands in the range 315–5,005 Hz;
5. The average level of one-third-octave bands in the range 80–1,000 Hz;
6. The peak level of the second resonance (around 200 Hz).

In the next subsection, the effect and influence of design and materials will be examined to understand the structure and acoustical relationship.

2.4.1 Design and Construction

Pioneering investigators such as Jansson and Meyer, as well as many others, have conducted experiments to single out the influence of different parts of the guitar to the overall sound quality. Meyer discovered using fewer struts, reducing the size of the bridge, varying struts spacing have “*desirable*” effects (Meyer, 1983).

Jansson created an order of importance list for different parts of guitar, bridge, top plate thickness and struts. Detailed overview of these three parts is presented in the next section, under the light of Meyer, 1983, Jansson, 2002, Caldersmith and Williams, 1986 and Richardson and Roberts, 1985.

2.4.1.2 Bridge, top plate thickness and bracing

The mass of the bridge has a significant effect on top plate. Heavier bridges have more stiffening effect on top plate, resulting a decrease in the frequency of first top plate resonance. Handmade Spanish Bridges are considerably lighter and less rigid (Jansson, 2002).

Top plate and strut thickness were studied by finite element method (Richardson and Roberts, 1985). The experiment started with top plate thickness being 2.9 mm, struts being 14 mm high, 5 mm wide. The results of their calculations showed that cross struts have large influence on the low frequency resonance. Reducing the thickness of top plate, significantly thinning the edge of the plate has greatest effect of all.

Australian luthier, Greg Smallman is famous because of using lightweight top plates, supported by lattice braces. He generally used struts of carbon-fiber-epoxy to balsa wood to achieve higher stiffness-to-mass ratio, high-frequency resonances ("lightness") (Richardson and Roberts, 1985).

2.4.1.3 Bracing

Bracing is the construction method to control the flexibility of top plate and its related motion to back plate. There are various designs acknowledged also some promising experimental approaches. Well-known designs shown in the Fig. 2.10 are traditional (a) fan bracing (Torres), (b) Bouchet, (c) Ramirez and (d) crossed bracing.

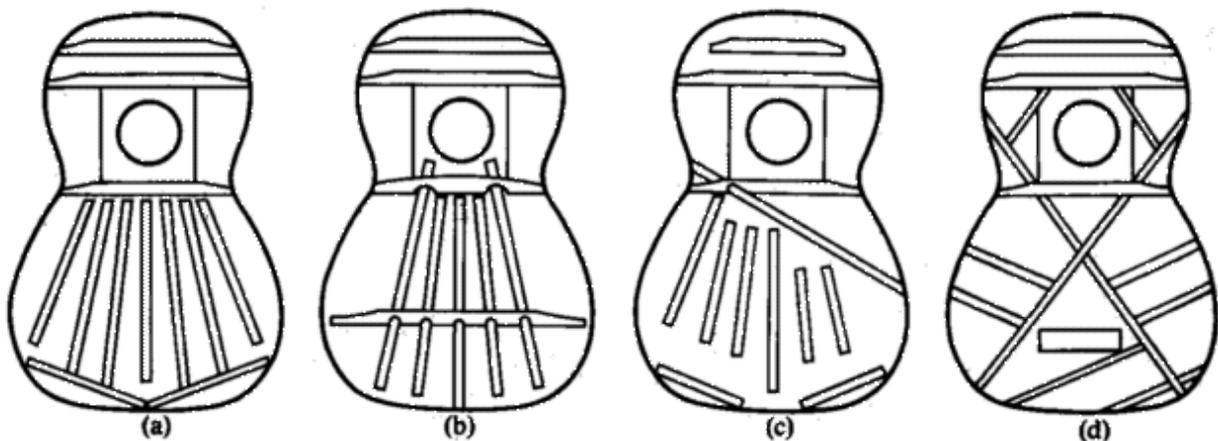


Figure 2.10 : Bracing designs

(Rossing, 2010)

Most of the classical guitars have symmetrical bracing designs, figure. 2.10 (a,b,d), however there are number of successful attempts of designing asymmetrical bracing systems. Hauser in Germany and Ramirez (Fig. 2.10c) are recalled primarily. They have introduced varying asymmetry to their designs, such as, use of shorter but thicker struts on the treble side to make the plate stiffer. Three of such designs are shown in the figure. 2.11. The most asymmetric and probably remarkable one of these designs was proposed by Kasha (1974), figure 2.11c, and

developed further by some of the famous luthiers such as, R. Schneider and G. Eban (Fletcher & Rossing, 1999b). Design of Kasha, has a split asymmetric bridge, struts of varying lengths are positioned close to each other. The waist bar bridges two long struts and the soundhole liner.

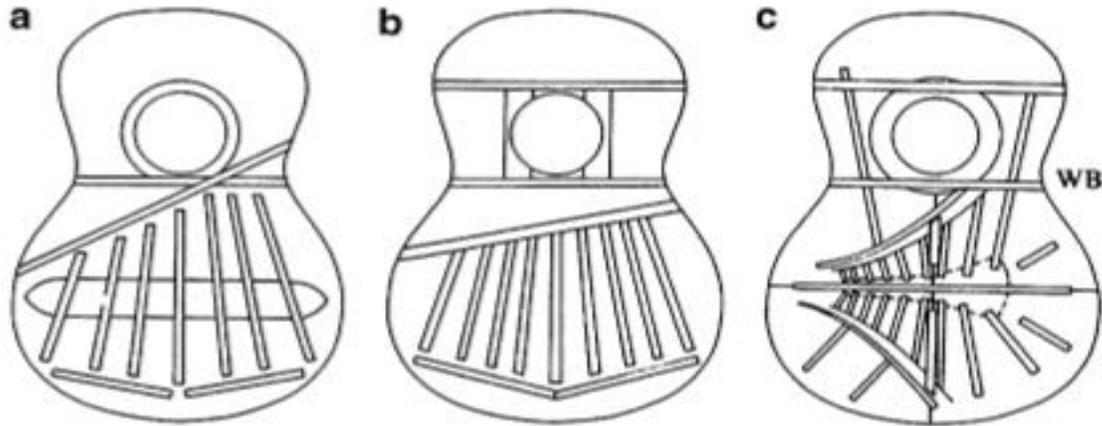


Figure 2.11 : Asymmetric designs.
(a) Hauser, (b) Ramirez, (c) Eban

2.5 Wood

Wood selection is the most important parameter in stringed instrument design. The body of a stringed instrument consists, in general, of a soundboard (top plate) and a frame board (back plate and/or side plate) (Yoshikawa, 2007). Several investigations and research have been concluded towards traditional choice of wood for string instruments (Bucur, 2006; Fletcher & Rossing, 1999a), and also some experimental studies for classifying acoustical properties of both traditional and untraditional choices of wood (Sedik et al., 2010; Timell et al., n.d.; Wegst, 2006; Yoshikawa, 2007).

This section addresses the components of woods regarding their acoustical quality. Instead of focusing on experimental studies with the aim of substituting the traditional choices of wood for string instruments, following section will examine why these traditional wood species were chosen by luthiers in the first place.

2.5.1 Acoustical quality of wood

The considered parameters for measuring acoustical quality of wood are stiffness, internal friction, density and in most cases wood texture for aesthetic concerns. One of the most plausible of these parameters is, c/p (Schelleng, 2005), where c denotes the propagation speed of the longitudinal wave along the wood grain, and p stays for density of the wood. Schelleng stated that both the inertia and the stiffness should be the same if the wood will be substituted with another one, to keep the vibrational properties same. Since the vibration of wood plate will produce sound radiation, c/p can be called “*vibration parameter*”, or “*radiation ratio*” (Yoshikawa, 2007). In addition to this, Schelleng found a strong correlation between the resonant Q value and c/p . The Q is the bilateral of loss factor, determined by internal friction

of wood. Given the significance of vibration damping in musical instruments, internal friction ($\tan \delta$) is especially relevant, being an essential material property, as opposed to other loss mechanisms such as by radiation. Dynamic Young's modulus E' and its ratio over density, E'/ρ called specific modulus (Brémaud, 2012), which is proportional to the square of sound propagation speed and of resonance frequencies of a piece of given geometry. The anisotropic features of these properties play a naturally important role in the vibration modes of plates and frequency spectrum (Bucur, 2006).

However, the contribution of wood to the functioning of different instrument parts often involves several properties, which can be combined in "material performance indexes." Frequently used indexes include;

$$z = c\rho = \sqrt{E\rho} \quad (2.5)$$

$$R = \sqrt{\frac{E}{\rho^3}} \quad (2.6)$$

$$ACE = \frac{\sqrt{E\rho^3}}{\tan \delta} \quad (2.7)$$

These indexes are studied by Schelleng(1963), Wegst(2006), Yoshikawa(2007) in detail. For an explanatory overview; (z), "characteristic impedance", is related to the transmission of one medium to another, from strings to soundboards or from soundboards to air for example. "Radiation ratio" described earlier, functions as average amplitude, or loudness. "Acoustical Conversion Efficiency", (ACE), is the ability to convert vibrations into sound pressure, shows itself as peak response.

2.5.2 Wood archetypes for string instruments

Stated in the early stages of this chapter, string instruments radiate through resonators. The string vibration is transmitted through a bridge to the soundboard. The material of the soundboard should allow for adequate transmission of energy from the string, and be able to radiate efficiently.

The choice of spruce resonance wood for top plate of guitar is made carefully, according to empirical rules (Bucur, 2006); A narrow grain spruce is preferred (2 mm annual ring width), although cedar of Lebanon or Canadian red cedar (*Tsuga heterophylla*) could be used as well as western cedar (*Thuja plicata*). Numerous studies are driven towards acoustical properties of woods for top of violins, but those results will not be suitable for guitar top plates, as guitars have considerably flat tops, unlike violins. Consequently, the stiffness required is different (Bucur, 2006; Wegst, 2006).

Spruce selected as high-grade has a quite low density ($\rho \approx 0.45\text{gcm}^{-3}$) and a very high specific modulus of elasticity (around $26 - 36\text{MPam}^3\text{kg}^{-1}$, leading to sound velocities up to 6000ms^{-1}) (Brémaud, 2012; Bucur, 2006). Internal friction of spruce is negatively correlated with radiation ratio. Considering acoustical performance, high E'/ρ , with a low density leads to high radiation

ratio (eq.2.6), and with low internal friction, higher acoustical efficiency (eq.2.7) is obtained. According to (Yano, Kajita, & Minato, 1994), from the point of view of coincidence frequency peaks of plates (100 – 250 Hz), high E'/ρ should ensure sufficient radiation in low frequencies (Brémaud, 2012; Bucur, 2006; Rossing, 2010). As a light material, spruce has moderate characteristic impedance (eq.2.5), which is advantage for sound transmission into the air (Wegst, 2006). The geometry of guitar blanks allows testing “by hand” damping and longitudinal/radial stiffness. Classification is just slightly better defined by basic acoustic properties than for violins (Yano et al., 1994). In the study of (Brémaud, 2012), she concludes these outcomes as follows : “Altogether, these different studies suggest that (i) wood selection and qualification by string instrument makers is by essence multi-criteria; (ii) the relative importance of mechanical -acoustical properties depends on the degree of freedom in the geometry of the instrument and/or of blank plates; (iii) properties of different instrument making grades can overlap, but form a distinct group within the *Picea abies* variability, with much higher than average E'/q and anisotropy, and low $\tan\delta_L$.”

Table 1: Acoustical properties of spruce with comparison to several species of Picea family.

(Brémaud, 2012)

Species	Distributional range ^a	<i>N</i> Sources	<i>N</i> specimens	ρ (g cm ⁻³)	E'/ρ (MPa m ³ kg ⁻¹)	$\tan\delta_L$ (10 ⁻³)
<i>Picea abies</i> (L.) Karst.	Europe (North, Central and Eastern)	9 ^b	1065 ^c	0.45 ± 0.04	28.4 ± 3.9	7.1 ± 1.2
<i>Picea engelmannii</i> Parry ex Engel.	North America (West Canada and USA, North Mexico)	2 ^b	2 ^f	0.4 ± 0.09	28.5 ± 0.7	6.3 ± 0.0
<i>Picea glauca</i> (Moench) Voss	Northern America (Canada and North USA)	1 ^c	3 ^e	0.46 ± 0.03	30.8 ± 3.2	7.0 ± 0.3
<i>Picea rubens</i> Sarg.	Northeastern America (Canada and USA)	1 ^c	14 ^e	0.48 ± 0.03	27.1 ± 7.8	7.6 ± 1.0
<i>Picea sitchensis</i> (Bong.) Carr.	Northwestern America (Canada and USA)	10 ^b	718 ^e	0.45 ± 0.05	28.7 ± 4.6	7.7 ± 1.5
<i>Picea brachytyla</i> var. <i>complanata</i> (Mast.) Cheng ex Rehd.	South China to North Myanmar and India	1 ^d	3 ^g		23.9 ± 2.5	8.0 ± 0.3
<i>Picea glehnii</i> (F. Schmidt) Mast.	North-Eastern Asia (Sakhalin, Kuriles and North Japan)	3 ^b	228 ^e	0.44 ± 0.03	29.0 ± 2.9	6.0 ± 0.6
<i>Picea jezoensis</i> (Sieb. et Zucc.) Carr.	North-Eastern Asia (North of Japan, China and Korea and Far-Eastern Russia)	6 ^b	166 ^f	0.41 ± 0.02	29.9 ± 3.0	6.3 ± 0.9
<i>Picea likiangensis</i> (Franch.) Pritzel	South-West China to Bhutan	1 ^d	6 ^g		27.2 ± 4.6	8.2 ± 0.7
Other woods of Pinaceae (26 species from 5 genus)	Northern hemisphere (+ Mexico, Mediterranean and S.E. Asia)	7	104 ^f	0.48 ± 0.08	22.1 ± 4.9	7.9 ± 2.0
Other softwoods (27 species from 15 genus in 4 families, Pinophyta)	Cosmopolitan (with different ranges and frequencies)	13	333 ^f	0.44 ± 0.11	19.1 ± 5.4	7.8 ± 2.4

Chapter 3

Methodology

In order to study the acoustical features of classical guitars, the study is divided into 3 stages: Measurement, classification and feature extraction from the chosen descriptors and acoustical property investigation. The results are examined to find a reliable difference that will suffice to distinguish guitars from each other while creating the foundation of the sound quality model that will be proposed based upon the features extracted.

3.1 Measurement

Two different recording techniques are used: Experimental modal analysis and sine-sweep and noise response measurements. The aims of these techniques are different, EMA (experimental modal analysis) is a vibration measurement method which is focused on the mode responses of the guitar top plate however capturing impulse responses by microphone array aims to preserve the “sound” of the guitar (nodes, anti-nodes), by obtaining the acoustical properties of guitar body.

3.1.1 Experimental Modal Analysis

EMA consists of a hammer (with a frequency response measurement capsule in the head), and an accelerometer being attached to the bridge of the guitar to capture the impulse responses created by the hits of the hammer. All equipment for this particular study is provided by Bruel & Kjaer.

The guitar is laid upon an absorption foam, inside a rectangular prism structure. Top layer of the prism is divided into points that are 1 cm away from each other, and each point is pierced so laser light can get through the layer to the guitar top plate, from the correct point, which shows where to hit hammer on. The overall setup is shown in the fig. 3.1.

Above the top layer of the structure, there lies a paper where the border of the guitar body is drawn, with the points, so the points in the paper and layer correspond to each other.

Limpid paper, square shaped is used to minimize the damage of hits, by putting between hammer and guitar for every hit. Frequency response of each impulse is displayed instantaneously on the computer screen, by the accompanying software. Even though it is impossible to keep the frequency responses same for every hit, as they are manual actions, momentary visualization creates an opportunity for correction and repeating the action for each impulse.

For every impulse, two frequency response functions are obtained, one for the impulse and second one for the response. Impulse response for Torres 625 at point 142 is shown in the figure 3.2. This measurement technique is applied on two Torres guitars, Torres 625 and Torres 626.

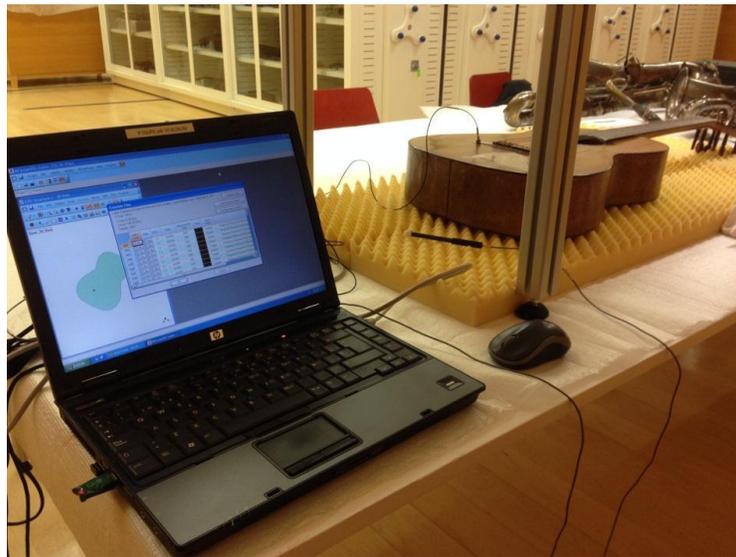


Figure 3.1 : Experimental Modal Analysis (Torres 625)

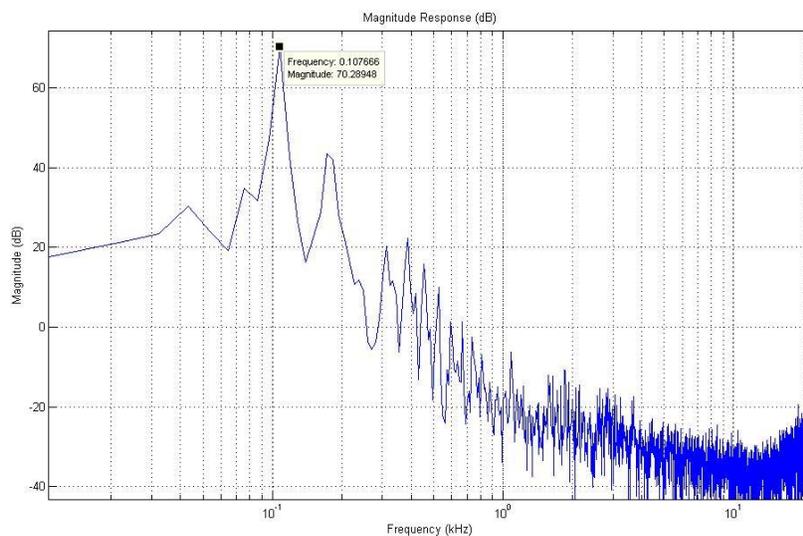


Figure 3.2 : Impulse response of Experimental Modal Analysis of point 14, Torres 625

In addition to vibrational and acoustical measurements, physical measurements are obtained from each guitar to use for the third stage of the methodology.

3.1.2 Sine-Sweep and Noise Responses

Second measurement method is based on sine-sweep and steady state response techniques usually used for room acoustics. Loudspeaker and an omni-directional calibration microphone is patched through the soundcard and connected to computer, being operated by designated digital audio workstation. Guitar is positioned as it is being played because of the microphone positioning concerns. Back plate is damped by absorption foam and strings are unattached. The surrounding environment is also covered with the same foam to reduce the noise and wall reflections. Loudspeaker is positioned in front of the sound hole while the microphone is inside the guitar body in two different positions as the signal chain illustration states in figure 3.3.

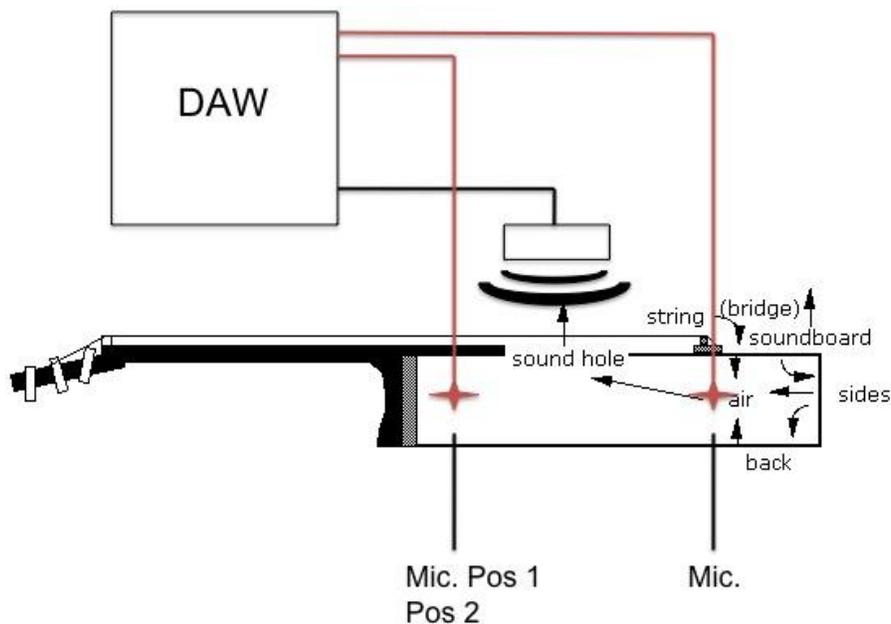


Figure 3.3 : Signal chain and microphone/loudspeaker positioning.

This measurement technique is applied on two different guitars, with 27 audio files generated for each position, consisting of white noises, pink noises, noise sine-sweeps, log sine-sweeps, linear sine-sweeps and impulses covering the frequency range 40 Hz-1000Hz to make sure everything needed is recorded.

Torres 625 and Labrador are the two guitars recorded. The latter one is chosen specifically for two reasons; it is going to be restored after the experiment, so the difference can be observed and secondly, it is a romantic period guitar which is apparently smaller in size so it will contribute to the physical aspects and acoustical investigation of this study. (Fig.3.4)



Figure 3.4: Recording setup for “Labrador”

3.2 Classification and Feature Extraction

For the second stage of the methodology, the captured audio files from both measurements are run through Essentia descriptors to Weka, to distinguish guitars from each other. The selected descriptors are used to extract features of the audio files in addition to the global spectral low-level descriptors. The intention is to observe the behavior of the descriptors towards these audio files, and choose the sufficient ones for the third stage of the study.

3.3 Acoustical Property Investigation

Third stage of the methodology aims to investigate “Physikalisch-Technische Bundesanstalt, Germany” proposal about sound quality prediction of guitars which is cited by Rossing, 2010; Meyer,1983; Jansson,2002; as well as many other minor publications related. The proposal is:

- 1.The peak level of the third resonance (around 400 Hz);
- 2.The average level of the one-third octave bands in the range 80-125 Hz,
- 3.The average level of one-third octave bands in the range 250-400 Hz;
- 4.The average level of one-third octave bands in the range 315-500 Hz;
- 5.The average level of one-third octave bands in the range 80-1000Hz;
- 5.The peak level of the second resonance(around 200 Hz);

These are the important aspects of guitar sound quality, as it is mentioned in the chapter 2. The proposal states that, the results of these aspects should be higher to achieve a high quality sound from a guitar.

“Sound Quality” statement is replaced with “acoustical property” in this study because of the guitars being worked on are historically important but old guitars. Their “sound quality” measures are related to time they belong to, and the technology and knowledge in those years.

The results of all these measurements and features will be presented in the chapter 4, results section of the paper, and examined briefly to build a sound quality model that relates the physical aspects, construction, type of material used and resonances of the guitar body.

Chapter 4

Results and Discussion

Before extracting the sound features of recordings, WEKA, machine-learning software is applied to classify guitars with Essentia descriptors as mentioned in previous chapter. Spectral features of the guitars are assumed to make real difference and this prediction turned out to be true in addition to ERB-Bands and Mel-Bands. The sine-sweep and noise recordings from the first position (under the bridge, inside the guitar body) are used. For the sine-sweep recordings the classification score with Bayesian algorithm is over 80%, and 75% for noise recordings. The successful descriptors are then used to extract features and investigate the “sound quality” model accordingly.

4.1 Feature Extraction

ERB-Bands and Mel-Bands descriptors are extracted from sine-sweep recordings for Torres 625 and Labrador for the 1st (Fig 4.1), 2nd (Fig 4.2) ERB-bands and Mel-bands (Fig.4.3) (“Physikalisch-Technische Bundesanstalt, Germany”) :

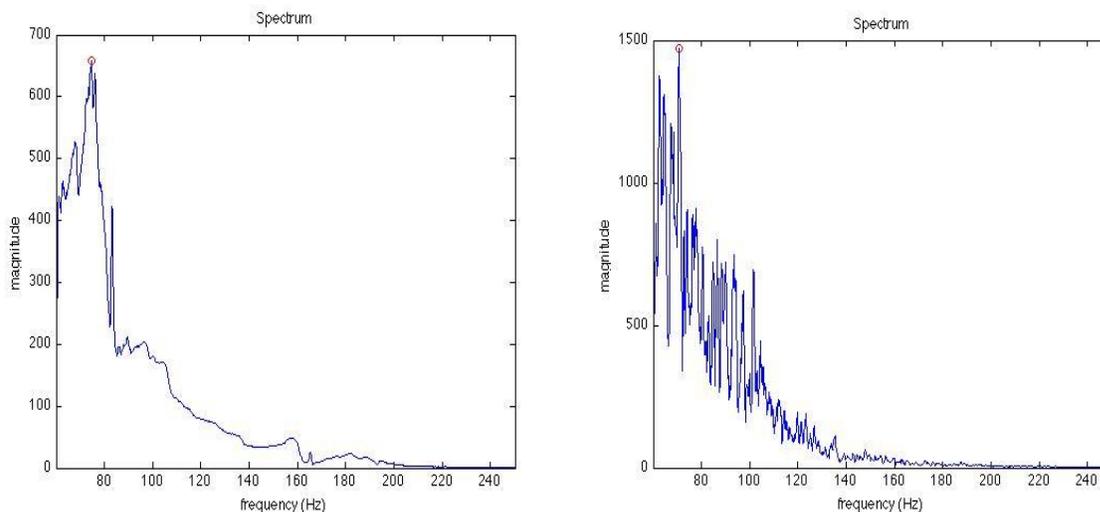


Figure.4.1 : Torres 625 (left) peak position at 74 Hz and Labrador (right) peak position at 71 Hz

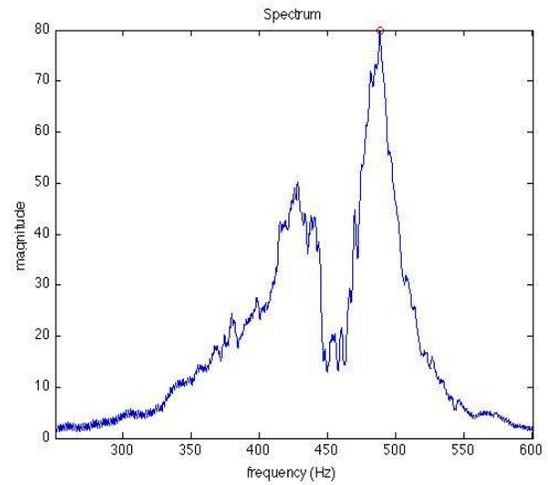
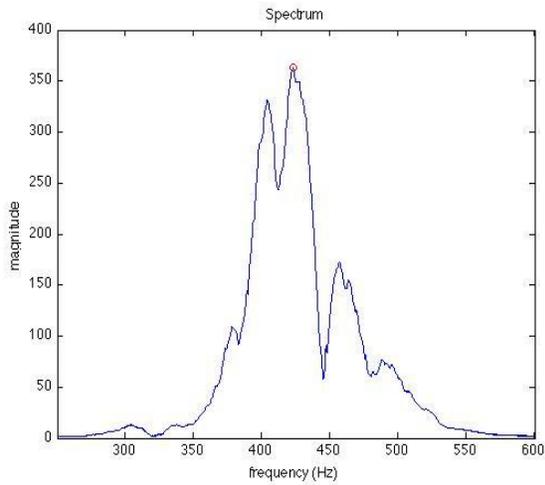


Figure 4.2 : Torres 625 (left) peak position at 423 Hz and Labrador (right) peak position at 488 Hz

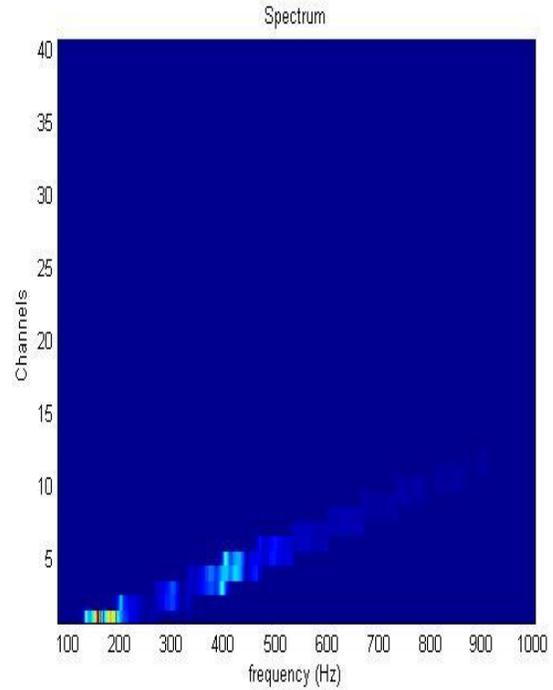
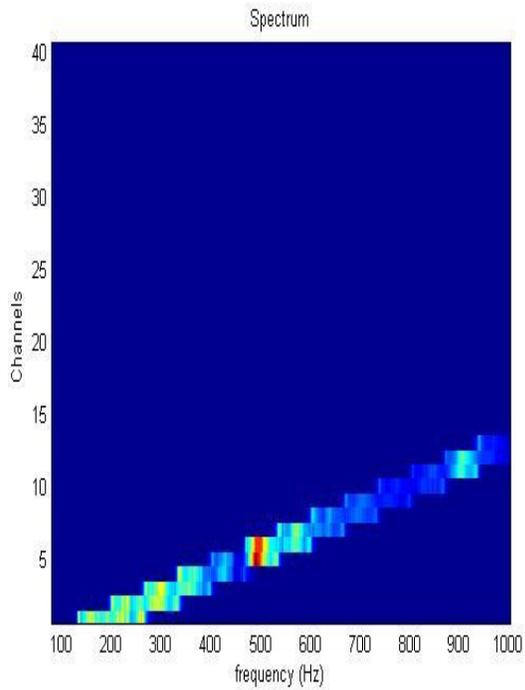


Figure 4.3 : Mel Bands spectrum plot for Torres 625 (left) and Labrador (right)

Spectral centroid, spread and variation plots are shown below in figure 4.4 for two guitars. Spectral flatness plots are also presented on figure 4.5.

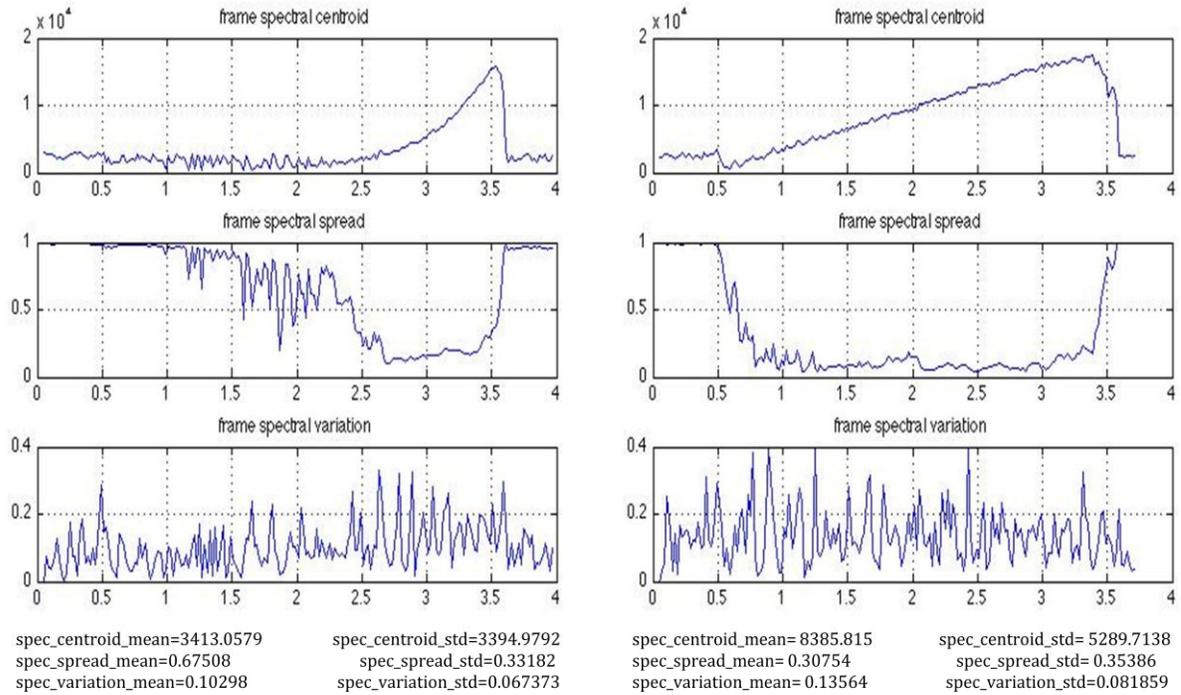


Figure 4.4: Spectral centroid, spread and variation plots for Torres 625 (left) and Labrador (right).

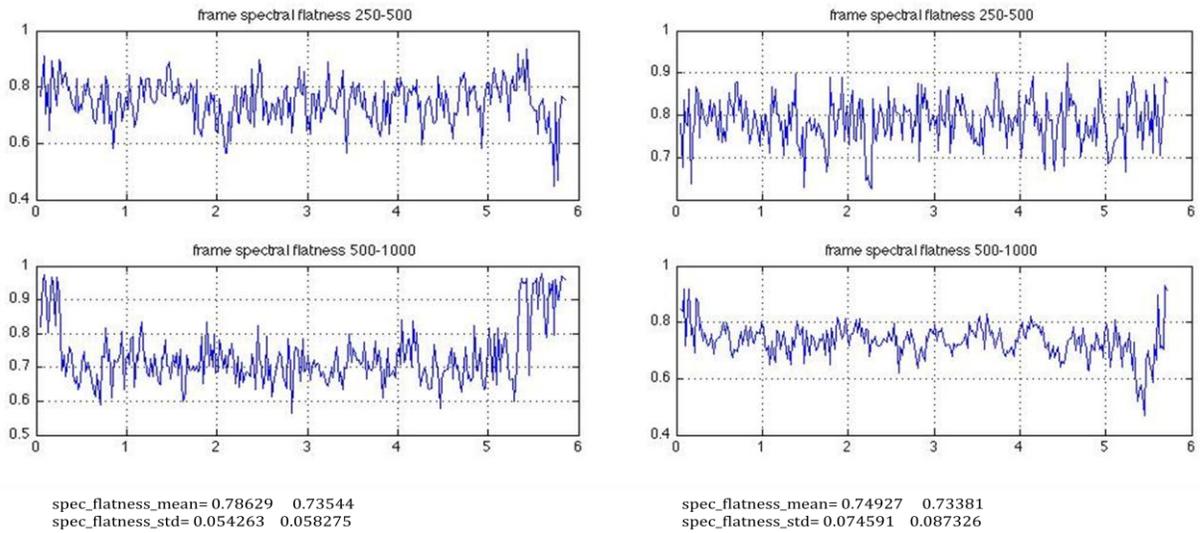


Figure 4.5 : Spectral flatness plots are presented for Torres 625 (left) and Labrador (right).

In addition to these information, the average levels of the 1/3 octave bands in the different ranges, spectral skewness, spectral kurtosis and peak levels of Helmholtz resonance, 2nd and 3rd resonances are computed and presented in the table below (Table 2).

Table 2 : Spectral features of Torres 625 and Labrador.

	Bracing	Helmholtz	2 nd Peak res.	3 rd Peak res.	E1	E2	E3	E4	SS	Skewness	Flatness	Kurtosis
Test Guitar	No bracing	110 Hz	214 Hz 0.6	394 Hz 0.4	0.0 2	0.0 1	0.1	0.1	0.49	0.47	0.5	2.62
Torres	Fan Br.	101 Hz	182 Hz 0.75	398 Hz 0.8	0.3	0.2	0.1	0.7	0.68	1.93	0.18	6.91
Labrador	Cross Br.	105 Hz	193 Hz 0.35	488 Hz 0.5	0.0 1	0.0 1	0.0 1	0.0 4	0.30	0.53	0.38	2.16

This table above summarizes the collected data cited from “Physikalisch-Technische Bundesanstalt, Germany”.

4.2 Physical properties

Physical properties of guitar bodies are also examined for the study. Relationship between the volumes of these three guitars is as follows:

$$\text{Torres 625 (V1)} > \text{Test Guitar (V2)} > \text{Labrador (V3)}.$$

The bracing of these guitars are; fan bracing (Torres 625), without bracing (test guitar), and cross bracing (Labrador) (Fig. 2.10). There are two set-backs which makes the bracing comparisons in this study invalid: (1) Test guitar is not constructed with a bracing inside, so the top plate and back plate are hold by ribs to each other only and (2) Labrador is in need of restoration (that is why it is chosen, so a second measurement can be applied after restoration is complete) so the bracing was not functioning properly when the recordings were made. The bracing types are still noted for preserving the information about the guitars which may be useful for further studies.

4.3 Wood type and material performance indexes

Literature review on the topic of the wood type and its acoustical performance as a “musical instrument” is presented in the chapter 2. Table 1. at the end of the chapter 2 presents common soundboard-quality woods used in string instruments production.

Sound board-quality woods are not only the best sound radiators of all, but they also have low characteristic impedance. A low characteristic impedance is beneficial in sound transmission into the air. The impedance of spruce (*piceae sp.*) is very similar to that of maple, the traditional material for the bridge, back plate and ribs. Maple also radiates sound well; its characteristic impedance is sufficiently high to act as a reflector for the air oscillations within the corpus of the instrument and to help them radiate into the room through the sound hole in the top plate.

Common beliefs are that regular playing of the instrument and aging of wood improves the acoustical properties of musical instruments. Guitars that are exhibited in museums have not been played for long time and it should be assumed that they are not in perfect shape regarding the aging of wood. However the new ones need to be “played-in”.

Humidity and creep are believed to play an important role in aging effect of wood on sound. Hunt and Balsan (1996), Beavitt (1996), Segerman (1996, 2001) presents several experiments in their studies regarding the “stiffness” and change in “loss coefficient” according to humidity. Summarizing the state -of-the-art in this chapter is necessary as this study involves museum instruments, which were being exhibited for some decades now. The effect of humidity and ageing is ignored for this study, so the default values corresponding to the wood type are used in the material performance index table below (table 3).

Table 3: Material performance Index and Size of Torres 625, Test Guitar and Labrador.

	p	E	z	R	ACE	Size
Test Guitar	X (Plywood)	X	X	X	X	V2
Torres 625	0.45	28.5	0.35	1.75	0.49	V1
Labrador	0.45	28.5	0.35	1.75	0.49	V3

4.4 General observations

The values represented in table 2, should be observed under the light of physics of string instruments briefly summarized in chapter 2. For instance, Torres 625, has a Helmholtz resonance frequency at 101 Hz, lowest of the three guitars. Flexibility of top and back plate, mostly related with bracing structure and size and wood type, states the range that a guitar is allowed to “breathe”. 1st resonance’s (Helmholtz) position, 101 Hz in this case, indicates that Torres 625 can be regarded as the “richest” guitar in spectrum among the other two. Spectral spread value and spectral kurtosis also supports this assumption.

Spectral skewness generally may be interpreted as high frequency component indicator. For guitars, the same value should be interpreted slightly differently. Guitar body resonances do not occur approximately above 600-800 Hz, as the string forces are not sufficient enough to vibrate the body. High spectral skewness values are indicators of the minimum low frequency responses of the plates (top plate in this case) because of the in-harmonicity of string instruments.

$$f_n = nf_0 \sqrt{(1 + Bn^2)}$$

(4.1)

The strings create harmonics approximately according to the equation (Harvey Fletcher, 1961), while guitar body emphasizes the upper harmonics of its own resonant modes (Fig 2.6, Fig 2.7). When they add up, they create a rich high frequency component which is impossible without a broad “breathing” range.

Test guitar has the highest value for Spectral flatness. Its lack of a bracing structure may be a substantial way to construe this observation. The bracing of top and back plate, emphasizes and enables coupling by increasing flexibility. The value of 0.5, being the highest among the three, indicates a flat spectrum (again a relative measure) shows a stiff body motion.

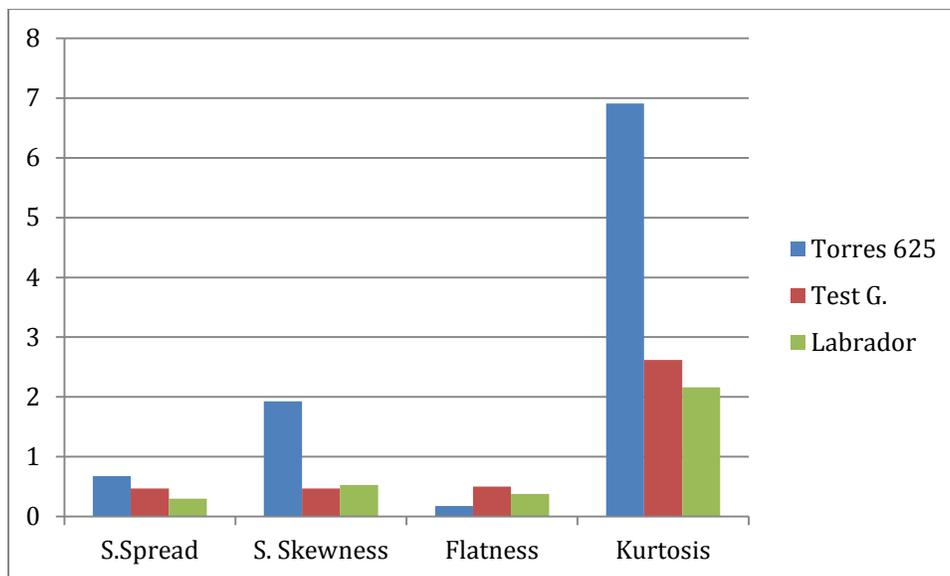


Figure 4.6 : Spectral descriptors' results

Level of one-third octave energy bands for four different bandwidths is part of the sound quality prediction proposal of “Physikalisch-Technische Bundesanstalt, Germany”, as stated in section 2.4. The main goal of this study requires to work on historical classical guitars, this prevents to investigate the sound “quality” of the guitars. Instead of a quality investigation, energy band and peak resonances are computed to compare guitars with each other. The comparison plot is presented in figure 4.7. Torres 625 has highest values for four bands. This supports the previous findings. Labrador and test guitar does not have any significant value in the first two bands and Torres and test guitar is almost identical in the 3rd band. Rich low frequency content of Torres 625 is already presented in table 2, with Helmholtz, 2nd and 3rd peak resonances. According to the sound quality proposal, higher values correspond to higher quality. As the physical state of Labrador and Test guitar does not allow making a valid prediction, the similarity

in the interpretation of spectral descriptor's findings and sound quality proposal may be perceived as promising.

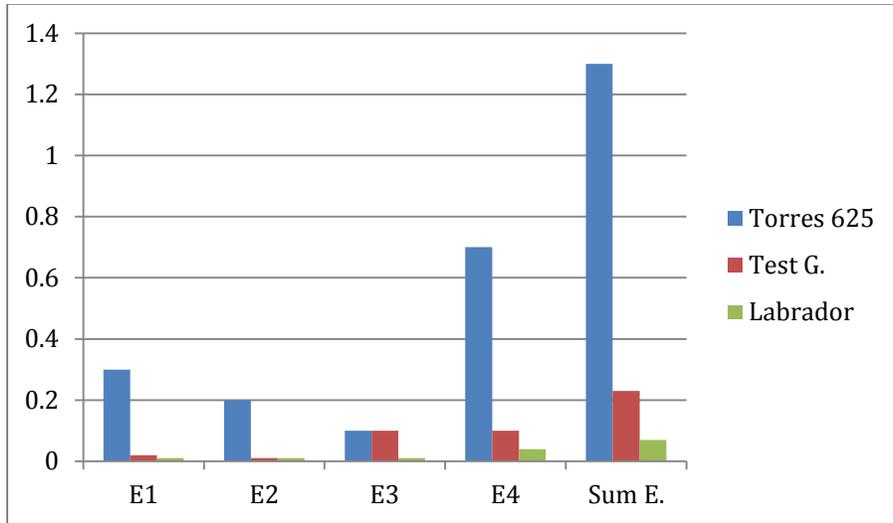


Figure 4.7: Level of 1/3 octave energy bands

When all the results and observations are summed up in one graph, by normalizing the maximum result of each category to 1, the comparison graph is obtained (Fig. 4.8).

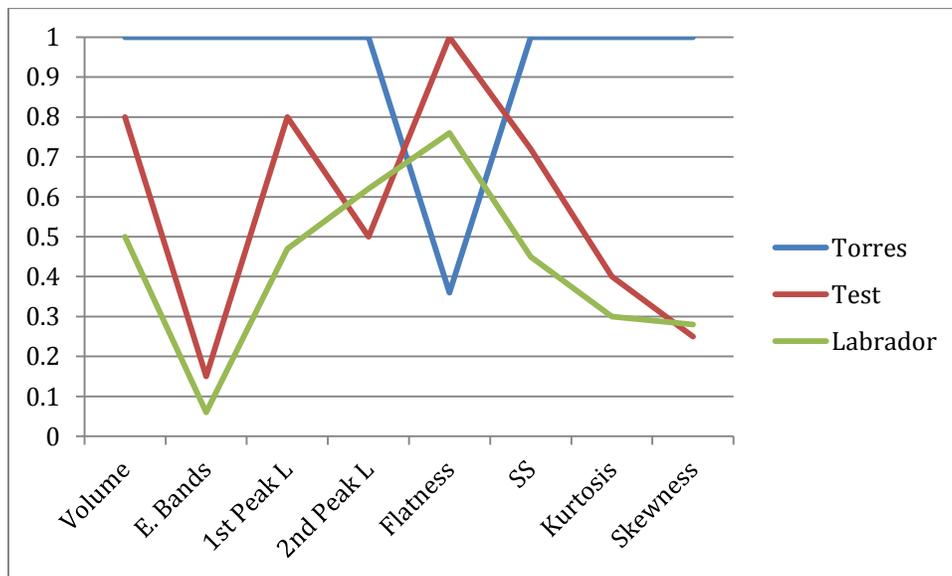


Figure 4.8: Comparison graph

Labrador and test guitar follow a similar pattern in the graph above, except 2nd peak resonance level. The reason for this exception as discussed before maybe the test guitar's stiffness, which the high value of flatness also points out.

First peak resonance level curves of these two guitars also differ from each other. This may be due to Labrador being a part of romantic guitar family. It is designed for shorter strings (approx. half of Torres) with a smaller guitar-body and so being incapable of creating standing waves in low frequency resonances (section 2.2.4).

These two differences are assumed in a way that they occur because of the physical differences mostly. The expansion of the data-set, including modern guitars with playable conditions, would create an adequate knowledge to be more precise about these predictions.

Chapter 5

Conclusion

The aim of this study is to propose a promising measurement and post-processing methodology that will create a foundation to predict sound aspects of guitars by their physical properties as well as to preserve and study the wood music instruments. The latter goal had practical challenges, as the instruments are fragile and unique museum instruments. This inconvenience directed the aim of the study to focus on a search for globally applicable methodology. The state-of-the-art already investigated physical responses, resonances and structural prospects of musical instruments. Finite-element method and experimental modal analysis are a couple well know examples of vibrational measurements. Instead of measuring the vibrations and modeling the sound features of instruments accordingly, this study aims to approach from an audio point of view.

5.1 Contributions

According to the goals defined in section 1.2, in the scope of this study following contributions have been made:

- A review of the state-of-the-art approaches to physics of string instruments, sound quality and wood material used in making instruments, effect of construction methods used to build string instruments.
- Collection of physical and acoustical data of guitars in Museu de La Musica.
- A method for measuring acoustical properties of historical classical guitars, without any potential of damage.
- Application of spectral descriptors to classify instruments by machine-learning.

5.2 Future work

Based on the findings of this study, following options would be ideal candidates for further work:

- Extending the dataset to be able to focus on acoustical effects of smaller physical differences.
- Apply the method on new and old instruments to predict the effect off humidity and “ageing”.

- Selecting guitars with same physical and structural properties as a data set to observe the machine-learning classification algorithms behavior on more complex tasks.
- Apply the methodology to instruments before and after restoration to observe the acoustical effect of the restoration procedure.
- Modify the method to make valid measurements of different string instruments, which enables to preserve sound features of historical instruments globally.

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