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Sound board's Frequency Response Analysis of Classical Guitars

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Resumo: A avaliação da qualidade sonora do instrumento é uma tarefa árdua de ser realizada computacionalmente. Este trabalho visa comparar características de qualidade entre instrumentos. A resposta ao impulso do violão é registrada no domínio do tempo e, por meio das Transformada Rápida de Fourier e a Wavelet Contínua, no domínio da frequência, são interpretadas as características de qualidade. Para discriminar alta qualidade, por meio da experimentação, os critérios são: 1) afinação das notas, projeção sonora e definição das notas; 2) equilíbrio sonoro em todas as frequências e timbres. A comparação da resposta de frequência (intensidade, densidade, forma, alcance) oferece boa informação quanto às características essenciais de qualidade dos instrumentos, de acordo com os critérios aqui definidos. Note que, entre os violões clássicos de alta qualidade, não é possível definir qual é o melhor de todos porque depende da percepção pessoal de qualidade do músico.

Palavras-chave: Violões Clássicos, Transformada de Fourier, Transformada Contínua Wavelet, Processamento de sinal.

Abstract: The instrument's sound quality assessment is an arduous task to be performed computationally. This work aims to compare high quality sound characteristics among instruments. The impulse response of the guitar is recording in the time domain and, by means of the Fourier and Continuous Wavelet Transforms the characteristics among high quality guitars, in the frequency domain, are shown. To discriminate high quality, through experimentation, the criteria are: 1) tuning of notes, sound projection and definition of notes; 2) sound balance at all frequencies and timbre. Comparison of the frequency response (intensity, density, shape, range) gives a good intuition regarding sound quality of the instruments that shares similar characteristics, according to the criteria defined. Note that, among the high-quality classical guitars, it is not possible to define what is better sound-wise due to the fact that high quality instruments are hearing-perceptual defined, therefore, depends on the criteria of the musician.

Keywords: Classical guitars, Fourier transform, Continuous wavelet transform, Signal processing.

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Evaluating a high-quality instrument is a difficult and subjective task, however, some instruments sound characteristics are essential for professional high performance guitarists. Perceptual hearing is the best tool for a musician to define what is intended by a high sound quality instrument. It is clear that each professional chooses his instrument according to his preference, where he prioritizes some aspects to the detriment of others. Therefore, when choosing an instrument, the musician determines a sound concept, as some sound characteristics will be striking according to the type of construction of the instrument (JANSSON, 1983).

The manufacture of a guitar that has all these characteristics is also an arduous task, and they are not all easily measurable. It is noted that different types of constructions lead to some particular characteristics. Nevertheless, a high-quality instrument is not an arbitrary decision based, only, on musician perceptual hearing; the high-quality instruments must share some essential physical characteristics. Computational systems cope with the analysis of an instrument based on frequency content and intensity, along with the shape of the frequency response that define important physical characteristics for a high-quality instrument. This work aims at answering the question: What is the difference between good and less good classical guitar instruments, based on the frequency response of the system (guitar), according to the criteria: 1) tuning of all notes, sound projection and definition of notes; 2) sound balance at all frequencies and timbre. The main focus in the evaluation here is the guitar project proposed by Torres (ROMANILLOS, 1997) around 1854 that shows variations over the years, including a modern instrument in the evaluation. Many luthiers follow this model, including Hermann Hauser I. Inspired by the guitars made by Santos Hernandez and Torres (ROMANILLOS, 1997; HURD, 2004), he started to adapt certain ideas in the timbre, high harmonics, and bass, rounder attack, and greater clarity. Torres thinks of a guitar prior to the classical guitar. A model that has a smaller body, a lighter structure and a less shiny and attacking sound, than classical guitars. But, on the other hand, sweetness, expressiveness, a sound that mixes delicacy, sophistication, expressiveness, and that allows variety of timbres (color), according to the change in the guitarist's touch, and its intensity and that has good sound projection. The main goal is to permit the reader, first, to have a good intuition of the quality of the sound of the instrument by looking at the frequency response and, second, an easy to reproduce experiment to help to assess the quality of the sound of an instrument.

The contribution of this work is related with the practical way to assess, with a low affordable price by using available software and piezoelectric pickups, that permits to get a good intuition about the quality of the instrument with respect to the criteria above defined. This methodology helps to choose a good instrument and, the understanding of the frequency response of the instrument, eventually, also helps to guide the manufacturing of the instruments and the performance of the musician. For the implementation, six different captured signals of the instruments: 1. a less quality instrument (TKG1) for reference; 2. Roberto Gomes 2002 # 173 (RG2); 3. Martin Woodhouse 2014 # 101 (MW2); 4. Sérgio Abreu 2008 # 544 (SA2); 5. Di Giorgio Romeo 3 1983 (DGR3); 6. Di Giorgio Master 1983 (DGM1) are analyzed with the help of an appropriate software (VoceVistaVideo R) and some pieces of code developed in R programming language, Rstudio™ [1]. The sound characteristic of the instrument is in the response of the materials to this vibration, attenuating certain frequencies, therefore, a filter, thus reducing the sound (OPPENHEIN e SHAFER, 2009). This vibration is captured by a microphone (COBBOLD, 2011) and is processing to generate the frequency content of the instrument for further interpretation. The process is pursued by means of characterizing the guitar by applying an impulse signal to the system (the guitar without strings). The generated signal (sound) is captured with a piezoelectric pickup, and it is processed by means of the Fast Fourier Transform (FFT) and Continuous Wavelet Transform (CWT) with Morlet basis[2] and this function response, in the frequency domain, would be of paramount importance to assess the quality of the instruments. Fourier Transform shows the frequency content of the instrument based on this vibration captured by a microphone in the time domain. The detailed mathematical discussion of the Fourier Transform and the perceptual hearing are out of the scope of this work and for the interested reader, please refer to (OPPENHEIMER e SHAFER, 2009; FLETCHER AND MUSON, 1933).

Therefore, the main focus here is the practical issue of having a good idea of the sound quality of a particular instrument after capturing and processing the emitted sound and how to interpret the results. The frequency domain signal of the instrument is utilized to compare the instruments based

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[1] Accessed in: https://www.rstudio.com/about/trademark/

[2] Accessed in: https://www.cs.unm.edu/williams/cs530/arfgtw.pdf

on three dimensions: 1) the magnitude of each frequency component of the signal; 2) the relevant components to characterize the signal; and 3) the spectral density and envelope shape of the function.

Differences among the instruments under consideration are perceived audibly in logarithmic function by the human ear, not discussed in this work due to the fact that it is out of the scope of this work. Additionally, discussing statistical methodologies is also beyond the scope of this research. The greater the amount of harmonics of the notes that resonate with the natural resonance frequencies of the top board, the more colored is the instrument and based on this, depending on what frequencies and what intensities are presented, the sound quality can be determined which is perceived audibly by the human ear, especially, by the more trained ones.

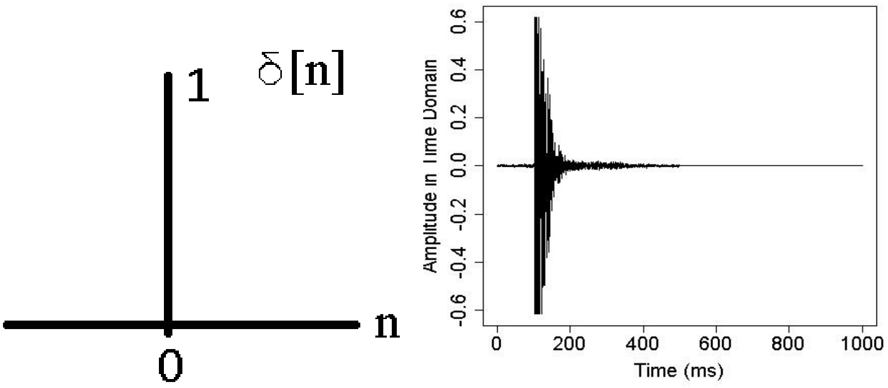
Comparison of the frequency response (intensity, density, range) of the instruments lead to a comparative ranking of the quality of the instruments under consideration, only with respect to the definitions of quality proposed here. As a conclusion, the largest the frequency response, the higher the intensity, shape (envelope) of the frequency function and its high density with the harmonics of the notes, the better the instrument. However, it is important to note that, the definition of what is a high sound quality instrument, depends on the musician's criteria based on personal perception. The results show that for the specific instrument under experimentation is clear what are good and less good instruments with respect to the criteria defined here. The rest of this paper is organized as follows: Section 1 summarizes the related work; Section 2 defines theoretical foundation; Section 3 addresses the system measure; Section 4 addresses the methodology and implementation; Section 5 presents the results and discussion; and finally, Section 6 summarizes the concluding remarks and future work.

1. Related Work

Instruments quality depends on aspects like: wood (HAINES, 2000 and METER, 2018), strings (BRADLEY, UM-HUO CHENG and STONICK, 1995), top plate response, etc. Those aspects are addressed in the literature in the fundamental descriptions of physical and mathematical issues of acoustic, structural, and historical aspects of guitars (KULKARNI, KAUSHIK, LOBO and SONKUSARE, 2020, ROMANILLOS, 1997). Analysis of the quality of the sound based on

Fourier analysis can be seen in (O'SULLIVAN, WINFREY and COWAN, 2007; SCHMIDT, MIGNECO, SCOTT and KIM, 2011) and to identify harmonic frequencies based on the vibrational analysis considering the guitar as a Symmetrical Mechanical System (STANCIU, VLASE and MARIN, 2019).

FIGURE 1 - Kronecker Delta; Impulse sound.



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A comprehensive development based on finite elements to characterize top plate sound response is presented and the same method is utilized for the manufacturing of a Nylon-String Guitar sound board (LUCAS and LEON, 2019). Mathematical models based on the Helmholtz Resonator and differential equations are addressed in (CAHAN, 1993; SONJA, DRAGON and MIRKO, 2012). Quality of the string and its tension are analyzed in (BRADLEY, UM-HUO CHENG and STONICK, 1995). Construction of high-quality instruments are illustrated in (JANSSON, 1983). In (ROMANILLOS, 1997) the Torres and Hauser traditional guitar construction models are addressed. Fletcher-Munson curves (FLETCHER AND MUSON, 1933) models the perceptual hearing, and further standardizing in the ISO 226 from the International Organization for Standardization is illustrated.[3]

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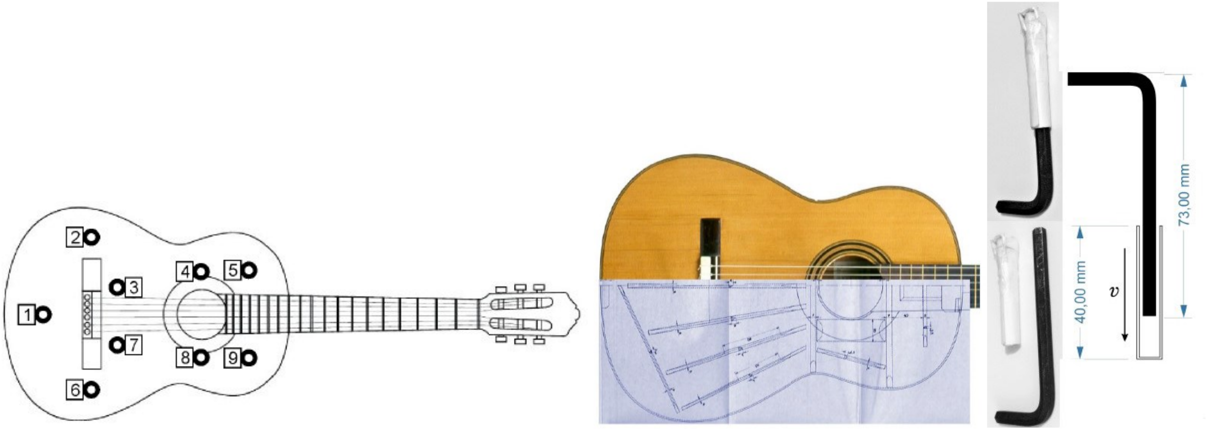
[3] Accessed in: https://www.iso.org/standard/34222.html

2. Theoretical Foundation

This work addresses the Torres and Hauser traditional guitar construction models (ROMANILLOS, 1997) along with an instrument that combines traditional construction with the so-called "modern", as the Roberto Gomes, where its harmonic fan is in trellis, its arm has a high scale, and the rest of the construction follows traditional patterns. The guitar project proposed by Torres around 1854 (ROMANILLOS, 1997) shows variations throughout the years. The most notable model, being formed by a sound board and body of *Picea abies* and *Dalbergia nigra* in most instruments. The sound board has seven support rods, its set is also called a harmonic fan (ROMANILLOS, 1997), and differing from previous Torres models with only five, see Figure 2 in the center. This is due to the reduction in thickness of the sound board so that the resonance was privileged. Many luthiers (HURD, 2004) follow this model, including Hermann Hauser I who built guitars in the Germanic style of the 19th century, with convex bottom, harmonic bars, wide body, but inspired by the guitars made by Santos Hernandez and Torres he started to adapt certain ideas in the timbre, high harmonics, and bass, rounder attack, and greater clarity.

FIGURE 2 - Collection Points; Torres Guitar Model; Pulse Generating Apparatus.



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In the instrument, that is the system under consideration, the sound board of the guitar vibrates at its natural frequency response. The sound characteristic of the instrument is in the response of the materials to this vibration, filtering certain frequencies (OPPENHEIN e SHAFER, 2009).

In order to obtain the characteristics of the system based on the frequency content of a continuous signal over time (the sound), it is necessary to perform four steps: The first is to capture the Impulse Response (IR) of the system, that models the presence in the input of all possible frequencies, i.e. as if all possible notes are played simultaneously (OPPENHEIN e SHAFER, 2009); the second processing is to transform the continuous time domain to the discrete time by means of samplings to be processed in the computer; the third processing is to transform from the discrete time domain to the discrete frequency domain to generate the frequency response. The fourth processing is to interpret the frequency spectrum to define the sound quality of the system.

The first processing is to apply the Kronecker delta signal to generate the Impulse Response (IR) of the system, just an impulse One in time equals Zero, and intensity equals Zero, otherwise; as shown in Figure 2 on the left. This is performed, see in the Figure on the right (pulse generator apparatus), as a sharp gentle hit at the bridge of the top board to avoid harming the instrument and capture it with piezoelectric pick-up (CUBBOLD, 2011). The IR characterizes the instrument, that is, it models all characteristics of the instrument.

FIGURE 3 - Normalized intensity of the Impulse frequency response Adimensional versus Frequency up to 14,000Hz.

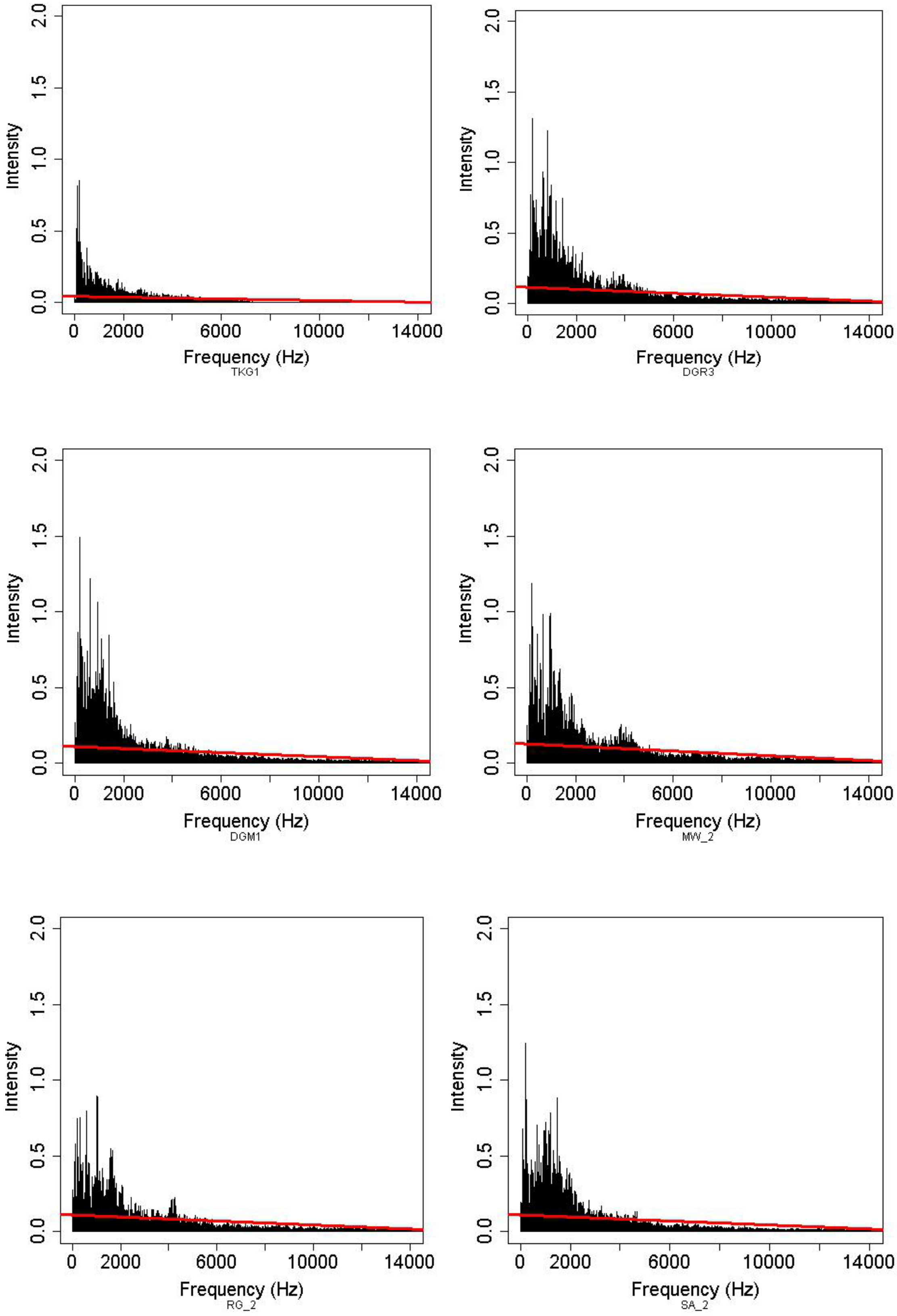

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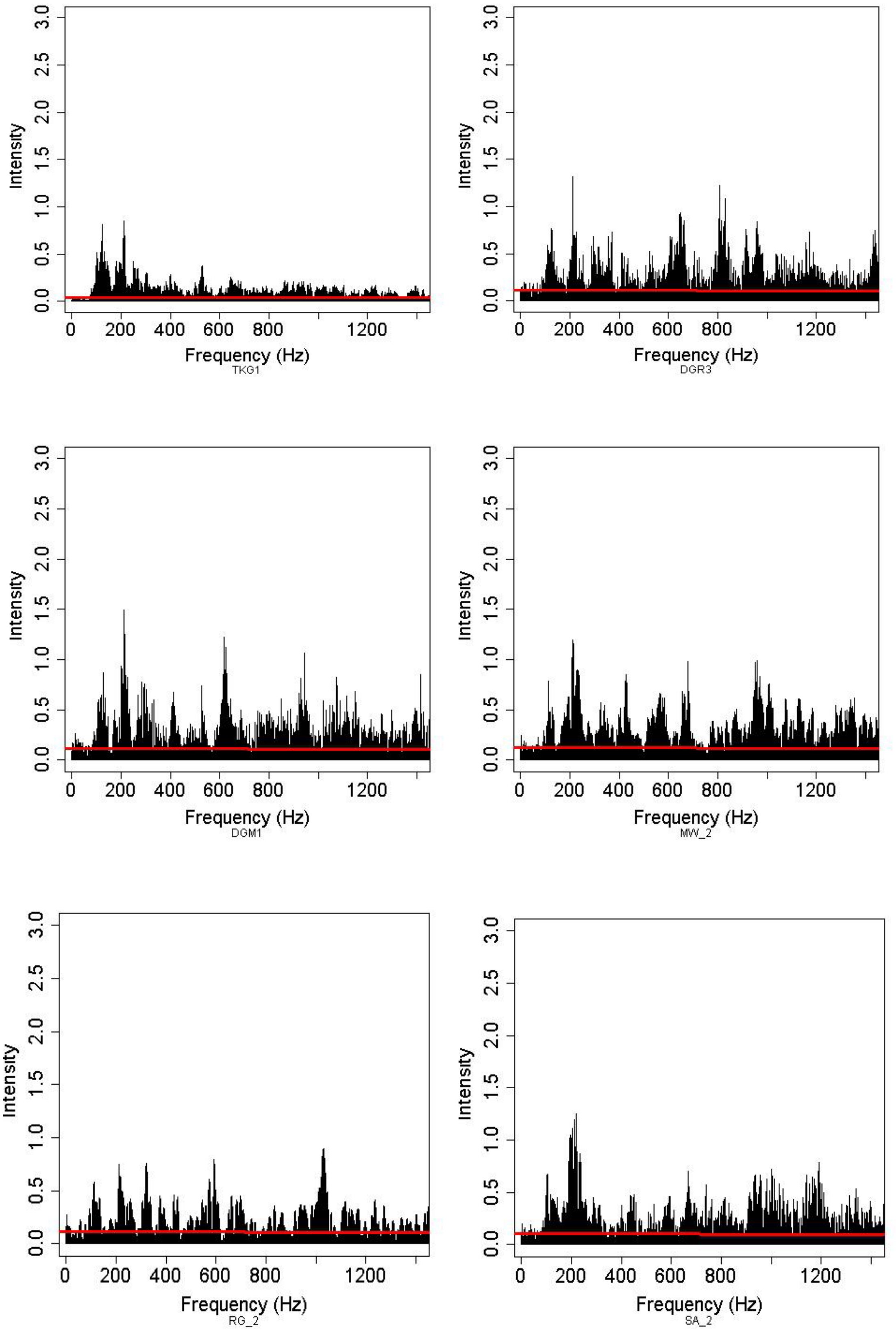
FIGURE 4 - Normalized intensity of the Impulse frequency response (RG) Adimensional versus Frequency up to 1400Hz.



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The second processing transforms the analogue IR captured to the discrete time by means of sampling, that is taking samplings of the continuous signal (the sound) at a sampling frequency defined by the Nyquist criteria (MARKS, 1991), that establishes that the number of samplings to reconstruct a signal must be, at least, twice the highest frequency of the signal. In this case, the highest frequency of the acoustic signal is 20,000 Hz. Of course, for the guitar is less than this frequency, as shown later.

The third processing is to find the frequency content of the IR, by means of applying the Discrete Fourier Transform and Continuous Wavelet Transform by means of the Fast Fourier Transform (FFT) and the Continuous Wavelet Transform (CWT, Morlets Wavelet)[4], respectively. The important concept here, for our purposes, is that FFT and CWT have the frequency content of the time input signal. What this equation, essentially, says is that the inputs signal, as for example, D major: E4=329.6Hz, C5=523.3Hz, E5=659.3Hz, G5=784.0Hz, C6=1047.0Hz, E6=1319.0Hz) and many multiples (harmonics) of each of those frequencies appear in the frequency spectrum, in theory, infinite of these, but in practice, appear only the ones that the quality of the instrument (mainly the sound board) permits, due to its resonance at some frequencies and the filtering in the other frequencies.

The fourth processing is to interpret the frequency content according to the defined criteria proposed here in next section to assess the quality of the system.

3. System Measure and System Implementation

Follows, the methodology proposed here to perform the measurements for the six instruments chosen above.

To acquire the sound, first processing step, a piezoelectric pickup (COBBOLD, 2011) is utilized to capture the impulse response of the sound board by applying the Kronecker delta which is generated by hitting in the bridge's guitar. The Kronecker delta is generated by utilizing the apparatus described in Figure 2 without harmful the system. The metal part is released from the same small height over the bridge in all measurements, producing a delta signal (pulse, instantaneous

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[4] Accessed in: https://www.rstudio.com/about/trademark/

sound). The piezoelectric pickup records the response of the sound board, as shown in Figure 1, Intensity versus Time, measured at the shown locations in Figure 2 on the left with 9 measurements taken in each guitar, 8 symmetrical and 1 asymmetrical.

For the computational system implementation, the acquired signals input to the VoceVistaVideo R software[5] to be analyzed. The data obtained in the program is subsequently processed with software written in the R programming by utilizing Rstudio™ environment.

For the second processing step, the data is processed by the computer's audio card and imported by pyaudio library in 3072-bit data blocks, with a sampling rate of 44110 samples per second. As established before the maximum audio frequency is 20,000Hz, therefore, Nyquist criteria defines 40,000Hz samples per second, but for practical reasons (including noise) there is an oversampling and it is, usually, utilized 44,110 samples per second for these kinds of applications. No filtered is performed to the input sound (impulse response), therefore, the environmental noise is presented, that is reduced by capturing the data in a noise isolated room.

For the third processing step, those signals are summed together in the time domain and transform to the frequency domain by means of the Fast Fourier Transform (FFT) (COOLEY, LEWIS, WELSCH, 1967) and the Continuous Wavelet Transform (CWT) calling in the Rstudio™, R programming environment, fft() and cwt() functions, respectively.

For the fourth processing step, the interpretation is performed based on the (FFT) spectrum, intensity versus time and plotting the complex number of the continuous wavelet transform in the complex plane, which are almost circular representations for each frequency presented in the CWT complex response, as shown in next section.

4. Results and Results Discussion

The impulse response of the top plate of the instruments were captured in the points defined in Figure 2 and processed by the FFT producing the Figures 3 and 4 for TKG1, RG 2, MW 2, SA 2, DGR3, DGM1 of the spectral components. In the vertical axis the normalized adimensional

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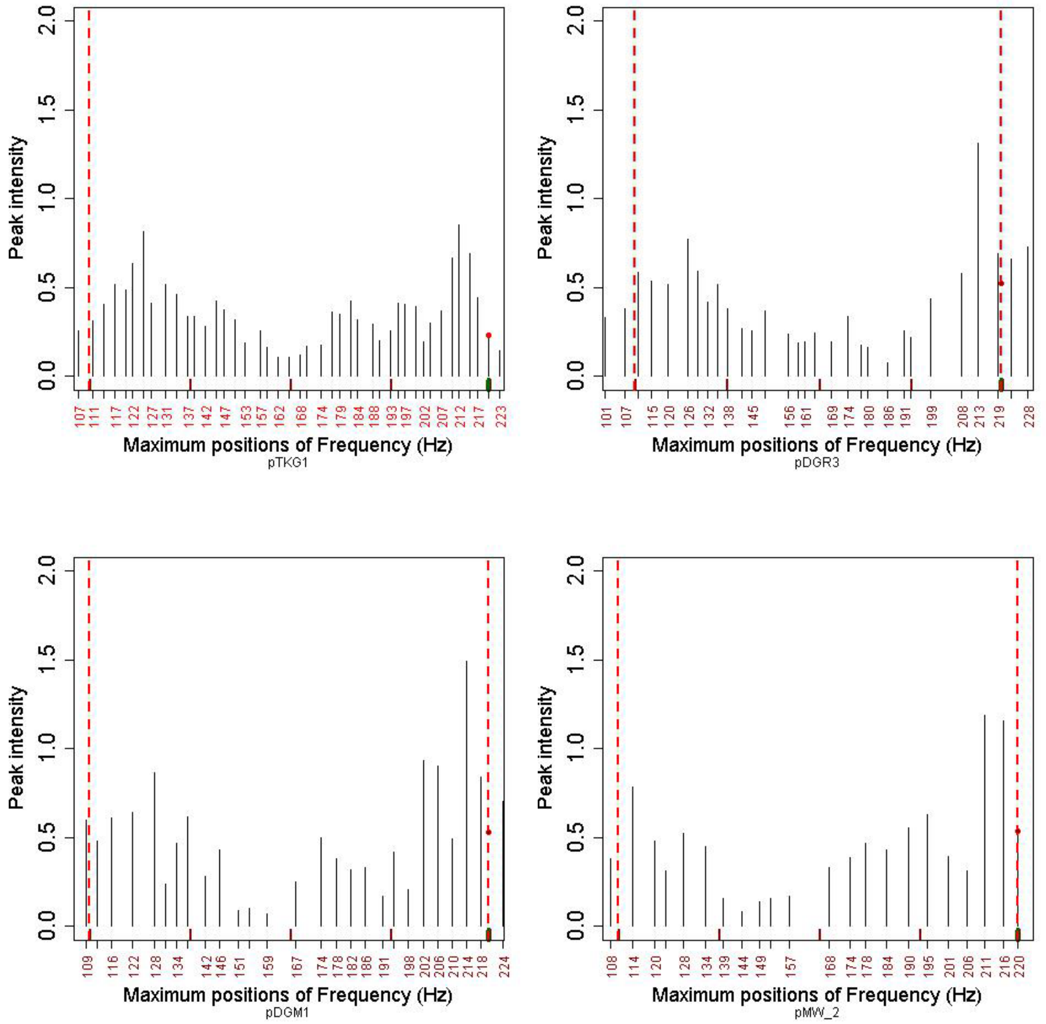
[5] Accessed in: https://www.sygyt.com/en/releases/vocevista-video-5-4-0/

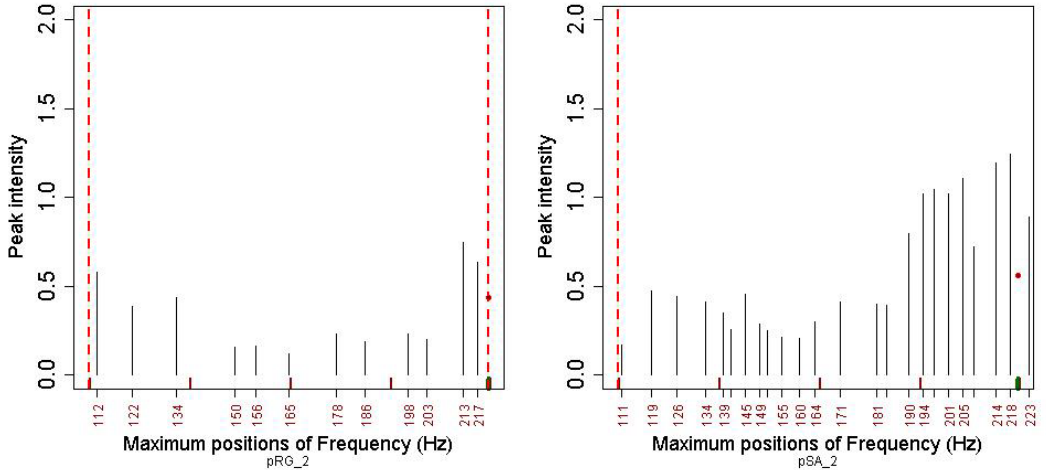
intensity versus the cycles per sec, Hz up to 14,000Hz and 1,400Hz, respectively, in the horizontal axis, shown next.

4.1 General Interpretation of Each Defined Characteristic

Let`s point out how to perform the first step of the interpretation of each characteristic in the frequency spectrum by defined four criteria, as follows.

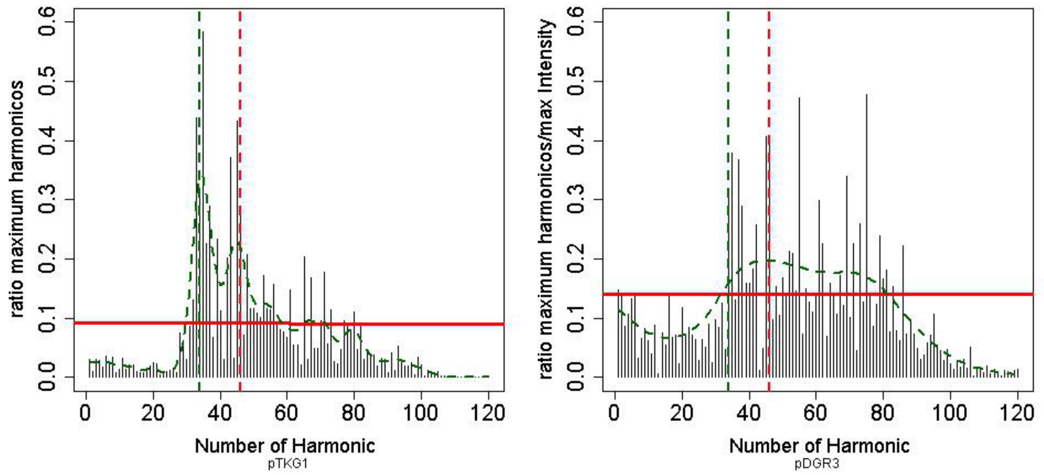
FIGURE 5 - Tuning of all Notes. Normalized Intensity of the Impulse Frequency Response Adimensional versus Frequency up to 220Hz.





Source: AUTHORS

FIGURE 6 - Sound projection: Harmonics 27.50, 55, 110, 220, 440, 880, 1,760, 3,520, 7,040, 14,080 Hz.



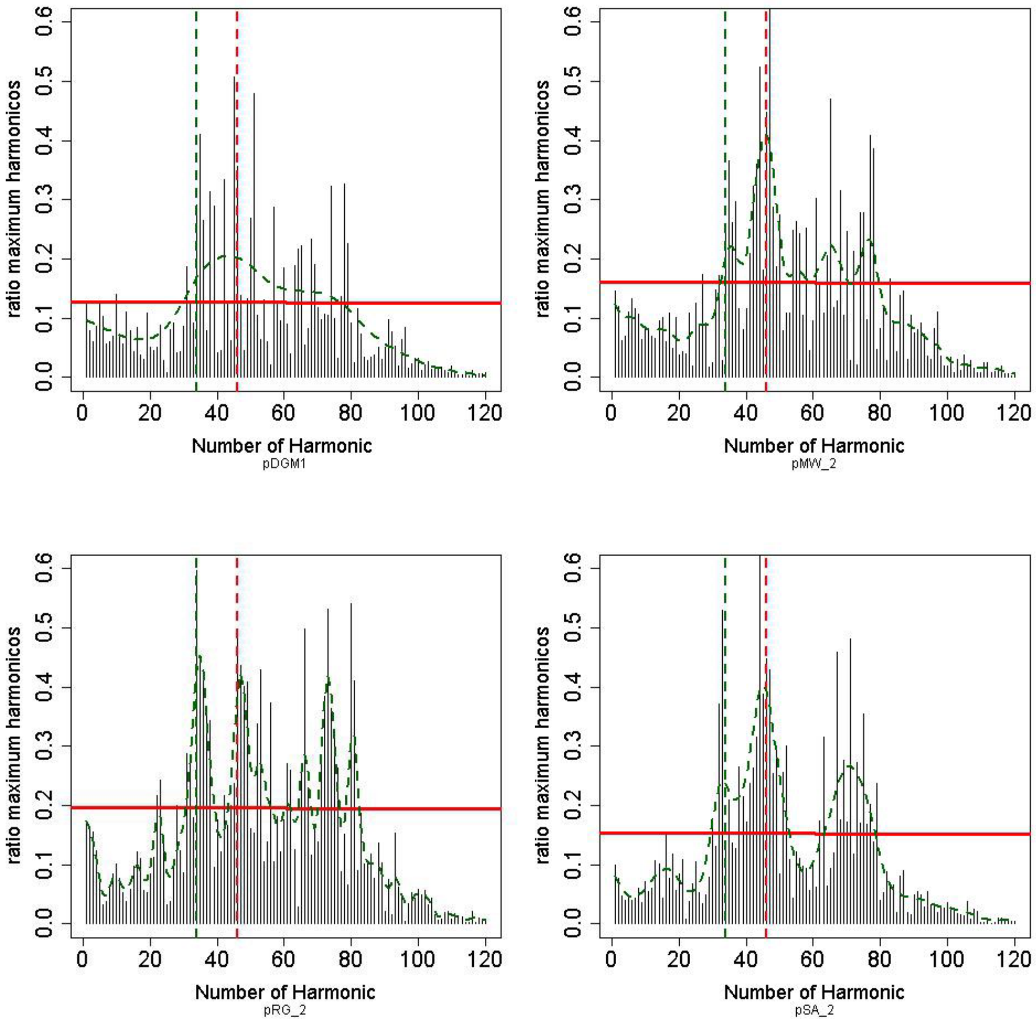


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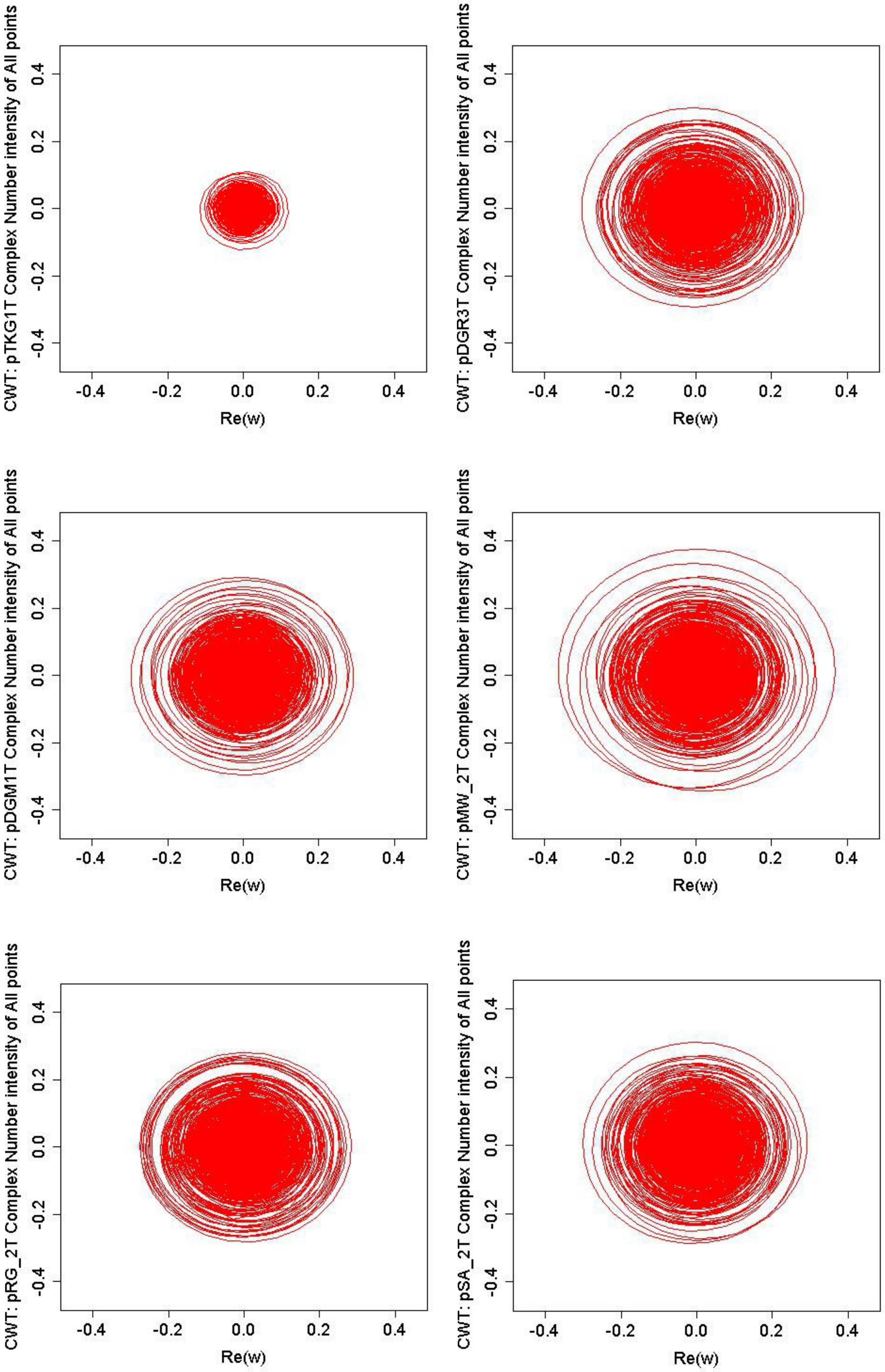
FIGURE 7 - CWT complex number: Imaginary part versus Real part.



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1. Tuning of all Notes.

In the frequency spectrum, search for the frequency of the note under consideration. Find the nearest peak in the spectrum from this frequency, there is one in the left and one in the right of that frequency. The more the distance in frequency between the frequency under consideration and the nearest peak in the spectrum, the less the capability of tuning for that note, for that instrument. Perform the same procedure for all notes.

As the top plate has its natural resonant frequencies that depends on the manufacturing process and quality of the wood, the frequency of the note will resonate at the natural frequency of the instrument, and then if those two frequencies coincide with the tuning is good, otherwise, the quality of the instrument for performing the tuning of all notes depends on how near those frequencies are separated.

As for example, for the harmonic of the note A at frequency 220Hz, if the top plate resonates (natural frequency at that frequency) there will be a high peak in the spectrum at that frequency.

2. The Sound Projection.

The more the number of the frequencies and amplitude (intensity) of the harmonics in the frequency spectrum, the more the sound projection.

Note that the sound projection appears in the relevant intensities in all the frequencies range, mainly, the high frequency that implies many harmonics of the notes, as for example, look at frequencies beyond 5,000 Hz and their intensity with low decay in intensity, as possible.

3. The Sound Balance.

The more the intensities of the frequencies in the frequency spectrum are equal for all frequencies, the more the sound balance. Note that the sound balance appears in the relations among all intensities of the frequencies (frequency spectrum), at all frequencies, this means that the intensity of the different notes needs, ideally, to be similar. As for example, look at frequencies that might be, ideally, with high amplitude, with no decay in intensity, shown by computing a linear regression in the spectrum. Of course, in the actual guitars, they never will be with equal intensity, as they decay in amplitude for high frequency.

4. The Timbre.

The more the number of harmonics of the notes with relevant intensities in the frequency spectrum, the more timbre (color) of the instrument. It appears in the number of multiples of the fundamental frequencies (harmonics).

Note that it appears in the density of the spectrum, as for example, let's consider G in the frequency spectrum appears 784.0, 2*784.0, 3*784.0, 4*784.0Hz and so on, up to many of these (ideally, infinite), same interpretation for all other chords.

4.2 Individual Interpretation of Each Defined Characteristic of Each Instrument

Extensive measures and processing for all instruments for different notes were performed, follows some results, for illustration purposes, of the methodology. Additionally, for the reader that is not familiar with the particular instrument, it is included instrument's descriptions from the point of view of a musician that characterizes the sound behavior and other features of the instruments under consideration. In the musician description regarding his perception of those criteria for the guitar under consideration, the qualitative expressions utilized corresponds to the numerical values for the quantitative evaluation, from 1 to 6, 6 being the better, as follows: 1 LIMITED; 2 less LIMITED; 3 FAIR; 4 GOOD; 5 VERY GOOD; 6 EXCELLENT.

1. *TKG1*: Less quality instrument.

The tuning of all notes is fair, as can be seen in Figure 5 that shows its frequency response. This is evidenced by looking at the marks: 1) noncontiguous red line of the frequency response at 110Hz and 2) the red point at 220Hz with the green mark in the horizontal axis at 220Hz and 440Hz, those are positioned at a distance in the horizontal axis from the peaks shown in continuous lines in black, which are the actual value in the frequency response. When the tuning is good for the A note at 110 Hz, 220Hz, and specially, at 440Hz a maximum peak must appear, and the marks coincides with the actual peak of the frequency response.

The sound projection is limited, as can be seen in Figures 3, 4 and 6, that shows the slope of the linear regression of the frequency spectrum, the red line, when it is close (ideally) to zero and the intensity (position in the vertical axis) is higher. Note that these two Figures show all peaks of the spectrum including noise and not only the harmonics of the actual notes, as in Figure 6.

The sound balance is limited, as can be seen in Figures 3 and 4 that shows its frequency response. This is evidenced by looking at the intense contrast in the intensity of the spectrum, that is, the (decreasing) slope of the red line generate by the linear regression of the frequency spectrum. Additionally, the position (intensity) of the linear regression in the vertical axis of the spectrum of the red line is not high.

The timbre is limited, as can be seen in Figure 4 that shows its frequency response. This is evidenced by looking at less relevant high frequency components (beyond 6,000Hz), making the sound less coloring with low density. When the timbre is good the number of harmonics and its intensity are higher. Additionally, Figure 7 shows the CWT in the complex plane. The Figure illustrates the frequency content in circular form for each frequency, i.e., each almost circular form corresponds to a frequency in the spectrum. It shows high density in low frequency (inner circles) and the density decays for higher frequencies (outer circles). The bigger the circle, the more frequency response and, of course, harmonics. Also, the density of the number of points to build the circle shows the high frequency response, when it is low, the lines which build the circle seem segments of lines.

The instrument has less quality, as evidence of the lack of some good characteristics as: density, frequency response and intensity.

Analogous analysis can be done, by the reader, for the other instruments based on the same Figures. The same analysis was done for other notes, not shown here.

For the sake of a summary of that analysis, Table 1 shows the authors intuition about those characteristics, by utilizing from 1 to 6 being 6 the better, to describe how well the particular characteristic for each instrument is. Note that, many instruments exhibit characteristics very similar to each other (as for example DGR3 and DGM1), nevertheless, for this visual interpretation, the authors do not classify any two instruments with the same quality number. For the comparative analysis among all instruments as a whole, a computational value is calculated and then, the most similar instruments are classified with the same number, as shown in next section.

TABLE 1 - Characteristic for Each Instrument.

Instrument	Tuning of all Notes	Sound Projection	Sound Balance	Timbre
SA2	5	5	2	6
RG2	1	6	3	5
MW2	6	4	6	4
DGM1	2	2	4	2
DGR3	4	3	5	3
TKG1	3	1	1	1

Source: AUTHORS

2. *Di Giorgio Romeo 3 1983.*

The tuning of all notes is good, as can be seen in Figure 5, as there is a peak very near to 220Hz and another peak near to 110Hz for the note A.

The sound projection is fair, as can be seen in Figures 3, 4 and 6, by looking at the slope of the linear regression and its intensity.

The sound balance is very good, as can be seen in Figures 3 and 4, by looking at the slope of the linear regression the more horizontal that is, its slope near to zero, and the shape (envelope) of the frequency response.

The timbre is fair, as can be seen in Figure 3, by looking at the high frequencies (number and intensity) of the frequency response.

This instrument has good intensity of the components of higher order in frequency response, this is a good quality instrument with frequencies in wide range presented in the signal that promote a characteristic brightness in the instrument's sound with good intensities.

3. *Di Giorgio Master 1983.*

The tuning of all notes is less limited, as can be seen in Figure 5, as there is a peak almost at 220Hz and another peak near to 110Hz for the note A.

The sound projection is less limited, as can be seen in Figures 3, 4 and 6, by looking at the slope of the linear regression and its intensity, which is almost exactly to the DGR3 with clear similarities in the shape, also.

The sound balance is good, as can be seen in Figures 3 and 4, by looking at the slope of the linear regression, that has an intensity very close to the DGR3, and the shape (envelope) of the frequency response.

The timbre is less limited, as can be seen in Figure 3, by looking at the high frequencies of the frequency response. This is almost the same as the DGR3, it is hard to established what is better, looking at the Figure, only; however, it can be done by looking to the actual number in the computational system, if it is needed, not shown here, but this idea is illustrated for the comparison among all instruments, in the next section.

This instrument has good intensity of the components of higher order in frequency response that defines a good sound projection and timbre. The timbre is good and less metallic, and it has good colors. This instrument is similar and better to the Di Giorgio Romeo 3 and an easy instrument to play.

4. *Martin Woodhouse 2014 # 101.*

The tuning of all notes is excellent, as can be seen in Figure 5, as there are ok peaks at 220Hz and another peak near to 110Hz for the note A.

The sound projection is good, as can be seen in Figures 3, 4 and 6, by looking at the slope of the linear regression and its intensity. This instrument is better, for this characteristic, than SA 2 and less than RG 2, with similarities in the shape with respect to the SA 2.

The sound balance is excellent, as can be seen in Figures 3 and 4, by looking at the slope of the linear regression, which has a very uniform intensity of the frequency response.

The timbre is good, as can be seen in Figure 3, by looking at the high frequencies. This is a traditional built instrument (based on the Hauser and Torres models) with a good volume (intensity), with a good range over a long distance. Its tone is, in general, crystalline with good possibilities of variation of tones. This instrument has good sound balance among the strings and in the different regions of the neck. It, also, has greater intensity of the components of higher order in the frequency response. The frequency of approximate resonance, higher peaks in the spectrum, presented in the signal, promote a characteristic brightness in the instrument's sound that contributes for the color and the beautiful timbre of the instrument.

This instrument has rich and sweet timbre, excellent volume and projection, clear sound and good sharpness, good sound balance between strings, easy to play, good sound support, when two or more notes are played together, they are well identified, characterized as a high-quality instrument.

5. *RG: Roberto Gomes 2002 # 173.*

The tuning of all notes is limited, for the note A under consideration, as can be seen in Figure 5, as there is a peak not near to 110Hz.

The sound projection is excellent, as can be seen in Figures 3, 4 and 6, by looking at the slope of the linear regression and its intensity, which is better than the others.

The sound balance is fair, as can be seen in Figures 3 and 4, by looking at the slope of the linear regression, which has low intensity in the range of 1,200Hz 1,400Hz of the frequency response in comparison with other instruments.

The timbre is very good, as can be seen in Figure 4, by looking at higher frequencies, but note that SA 2 has a better frequency response than this instrument. This is an instrument that combines traditional construction with the so-called "modern". This instrument has relevant components of higher order making the sound coloring, characterizing a rich and sweet instrument's timbre with good capabilities in all regions. That was expected, since the instrument has very good wood quality and construction. Its harmonic fan is in trellis, its arm has a high scale, and the rest of the construction follows traditional patterns. It has excellent intensity and sound projection with a full-bodied timbre. It has few variations of timbres, that is, some changes in the touch on the part of the guitarist do not, significantly, alter the timbre of the instrument.

This instrument has very good power combined with a full-bodied, rich, sweet and volcanic tone with very good dynamic response. The instrument presents good balance, but some notes sound more or less when compared in different regions of the instrument's neck, but evidencing by the extensive results observed. It does not have so many nuances of timbre and sharpness.

6. *Sérgio Abreu 2008 # 544.*

The tuning of all notes is very good, as can be seen in Figure 5, as can be seen in Figure 5, as there are peaks near to 110Hz and 220Hz for the note A.

The sound projection is very good, as can be seen in Figures 3, 4 and 6, by looking at the slope of the linear regression and its intensity less than RG 2, but better than the others.

The sound balance is less limited, as can be seen in Figures 3 and 4, by looking at the less uniform intensity in the higher peaks near to 200Hz and 1,200Hz and lower peaks at 1,400Hz of the frequency response in comparison to other instruments.

The timbre is excellent, as can be seen in Figure 4, by looking at the higher frequencies that has the wider range, among all instruments.

This is a traditional built instrument (based on the Hauser and Torres models) characterized by a medium to good volume (intensity), with a long-distance range with excellent definition (sharpness) of the notes.

The instrument has exceptional sound balance between the strings, which means that there are no major differences in intensity and timbre between the strings throughout the region of the instrument's neck. This instrument has greater intensity of the components of higher order in frequency response, which contributes to the characterization of the instrument that contributes for the color, brightness, and the beautiful rich and sweet timbre of the instrument. This is a high sound quality instrument.

This instrument has a good volume and projection, excellent clarity and sharpness (distance, sharpness and identification of two or more simultaneous sounds are excellent), also, excellent balance between strings, medium playability, good sound sustain.

The instrument has a wide variation of timbres, and very sensitive to the guitarist's touch, that is, the slightest change in the touch, the timbre changes, that is, the slightest change in the angle of attack of the right hand, there is a change in the timbre of this note. The same happens with the left hand, that is, a small deviation in the placement of the fingers of the left hand, generates a change or failure in the sound production. This is one of the reasons why it is considered a difficult guitar to play, any change in the production of the sound, it denounces.

4.3 Comparison of the Defined Characteristic Among the Instruments

Let`s point out how to compare the frequency spectrum taking into account the harmonics of the notes, only, among the instruments.

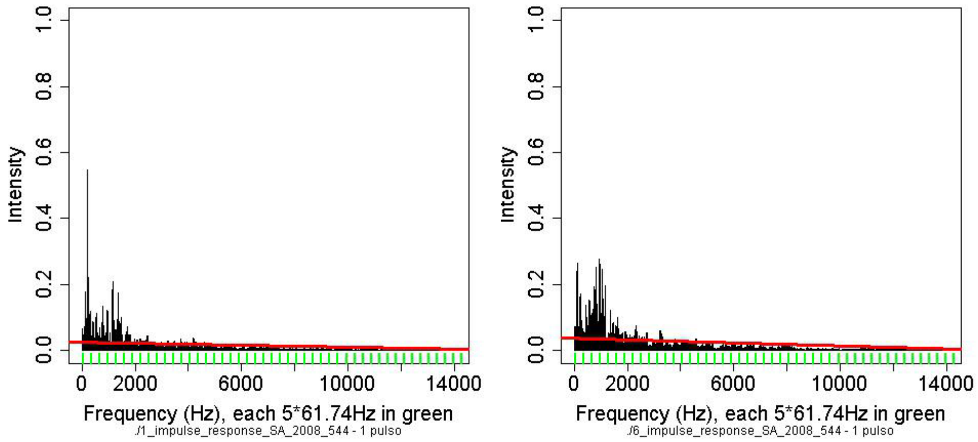
In all Figures discussed so far, it is visible in the images of the Fourier transform (frequency spectrum), that there is a strong resonance (see the intensity in the vertical axis), around 220Hz, as expected, due to the resonance of the sound board. Strong components are also present between 600Hz and 1,000Hz, with less intensity for the less quality instruments, as for example, see Figure 4. Note the difference among the instrument in higher frequencies.

Additionally, for illustration purposes, see the Figure 8 for the Sérgio Abreu in points 2 and 6, the frequency response of the symmetric points is very similar, but presents differences for high quality instruments (points 2 and 6, 3 and 7, 4 and 8, 5 and 9), not all of them shown here.

The authors' comparison among the instruments, are classified by means of numbers from less quality instrument 1 up to 6 the better one, as before.

Numerical values on the right of the table. Intensity Sound Y= 45.45 X-2.45; Frequency Balance Y= -0.000798722 X + 7.194; Tuning in all Regions Y = 0.0007985945 X - 0.01661. Where Y, X stand for the axis of the coordinate system to calculate proportions from 1 to 6 (Y) according to the measured results (X).

FIGURE 8 - Sérgio Abreu Intensity of the Spectrum at Points 2 and 6.



Source: AUTHORS

TABLE 2 - Characteristic for all Instruments.

Instrument	**Frequency Balance**			**Intensity Sound**			**Tuning in all Regions**		
SA2	4	4178	4	2	0.138	4	4	3957	4
RG2	6	1494	6	4	0.169	5	6	1273	6
MW2	5	3961	4	3	0.169	5	5	3740	4
DGM1	3	5092	3	6	0.186	6	3	4871	3
DGR3	2	5258	3	5	0.17	5	2	5037	3
TKG1	1	7755	1	1	0.0766	1	1	7534	1

Source: AUTHORS

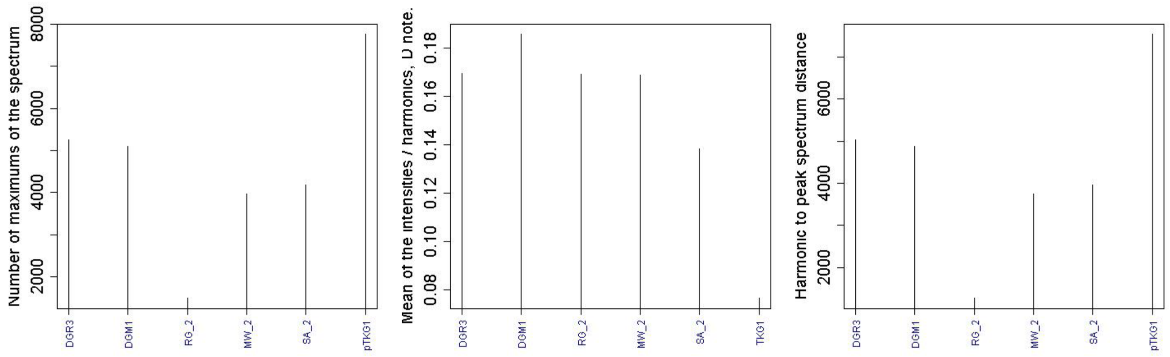
To define an order in quality for all the instruments in just one number, three more criteria named here: Frequency Balance, Intensity Sound and Tuning in all Regions, that capture additional important physical characteristics of the system, are also proposed.

Frequency Balance: It counts the number of maximums of the spectrum, the higher the number, the better the instrument.

Intensity Sound: It measures the mean of the intensity of the spectrum, the higher the mean, the more volume of the sound of the instrument.

Tuning in all Regions: It measures, in the frequency domain, the distance between the frequency for the note under consideration and the frequency of the actual maximum peak in the spectrum, nearest to that note. For example, 220Hz of the harmonic of the note A, then, in the spectrum there are two maximums near 220Hz one to the left and one to the right. The nearest is chosen and this distance, in frequency and that is taking into account for this measure. The more distance, the less accuracy in the tuning of the instrument. Note that, this is the same process for the tuning of all notes. Additionally, this process must be performed for the same note playing by pressing different chords at the correct frets in the whole neck's guitar. As for example, for the E note, for the open first chord, measure the distance, after that do the same for the second chord pressed in the fifth fret, and for the third chord in the tenth fret, and so on.

FIGURE 9: *Frequency Balance. Intensity Sound. Tuning in all Regions.*



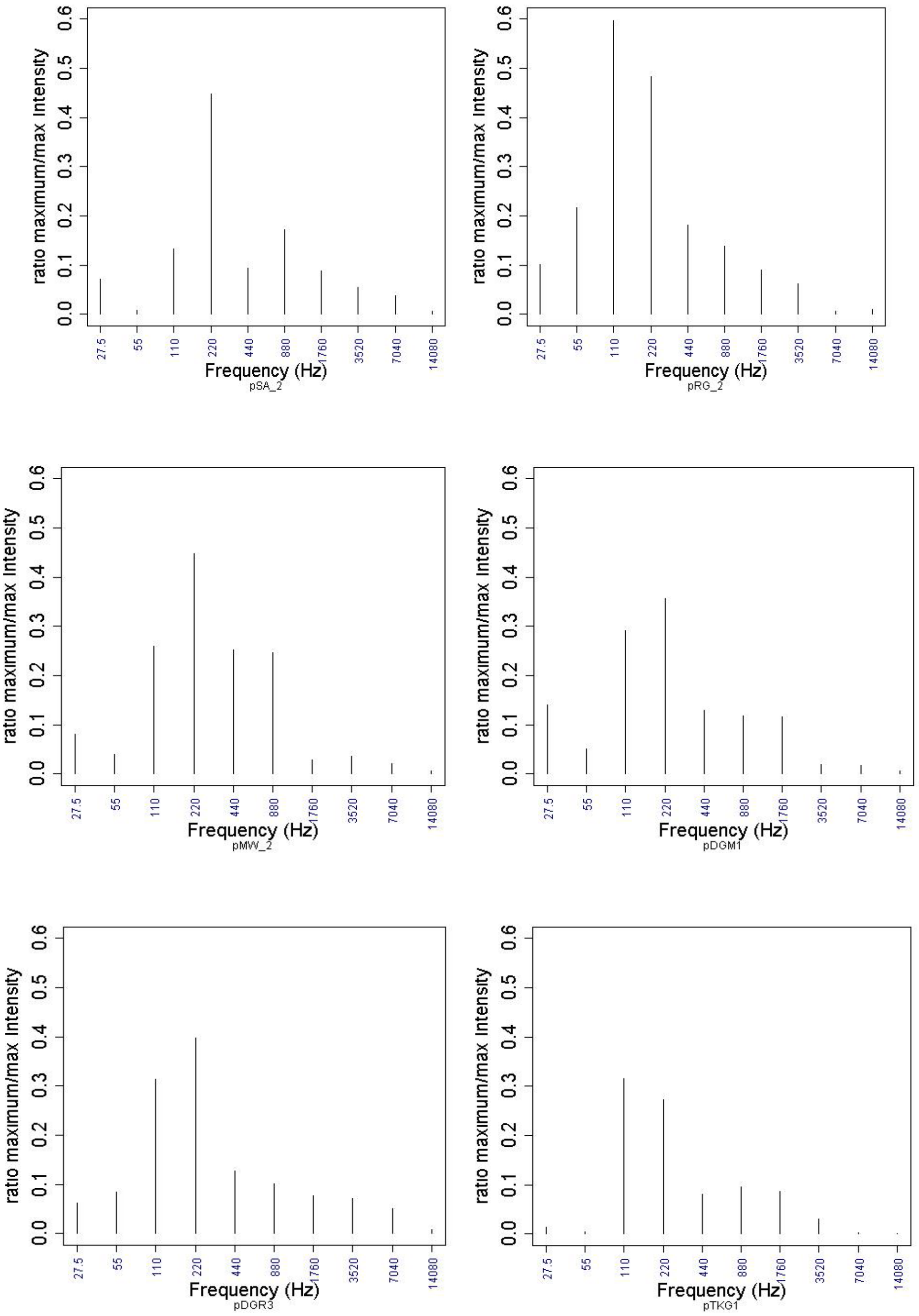
Source: AUTHORS

Figure 9 shows the number of maximums of the frequency response taking into account the harmonics of the actual notes, only. A good instrument shows many maximums positioned at the harmonics of the fundamental notes, due to the notes are periodic signals. Therefore, frequencies different from the multiples of the fundamental note (harmonics) are considered noise.

Figure 9 shows, from left to right and from top to bottom, the Frequency Balance, Intensity Sound and Tuning in all Regions, respectively. As we can see in the Figure 9, the instrument that has a greater balance in the intensities of the harmonics has the possibility of a greater balance between the low and high notes; this is the slope of the linear regression (red line in the spectrum).

The variety of timbres is, also, generated from this balance of harmonics that the instrument has, when the instrument presents higher frequency response. The DGM and DGR guitars have a little less than the previous ones and the RG 2 is the least balanced among them. It can be noticed, that it has a sharp peak in its fundamental, but the intensity of the other harmonics is lower.

FIGURE 10 - Harmonics



Source: AUTHORS

Figure 10 shows the normalized maximums peaks of the harmonics of the notes up to 14,000Hz. The higher the ratio and the more numbers of peaks in the Figure, the better the instrument. Note that, the RG instrument has a significantly higher intensity than the other instruments. The SA, DGR3 and DGM1 guitars are equivalent and the MW slightly smaller. This reveals that the RG, for having a non-traditional construction, has among its characteristics greater sound volume compared to the so-called traditional instruments.

It is noted that the guitar that best represents these characteristics is the one that contains more harmonics, as can be seen in Figure 10 for each instrument in the intensity of the peaks with higher intensities that the human ear can perceive, that is, the more frequencies can be heard, the more the instrument is characterized as high quality and balanced, as its envelope encompasses a large amount of perceived harmonics. This sophistication that the guitar might have, allows the musician to extract variety timbres and nuances, enriching the musical aesthetic possibilities.

Analogously, as it was shown in the Figure 5 for the Tuning of all Notes, the Tuning in all Regions of the instruments is analyzed and compared, by taking into account proximity of the frequencies of the notes through the whole instrument's neck. For instance, as well known, the open chord E, first one, must sound the same as the second chord in the fifth fret. It is, also, well known that a perfect pitch in all regions of the neck of the guitar is physically impossible and also not desirable.

Table 2 shows the comparison of all instruments under consideration taking into account the above characteristics, ranking from one (less quality) to six (best quality), as viewed by the authors as calculating by the software.

From the measurements carried out in this work, we have some directions according to the evaluation criteria for a good and less good instrument. Such as a choice for one instrument or another depends on the characteristics that the musician is looking for. Of the instruments analyzed and compared, if someone is looking for an instrument with more volume and sound projection, they might opt for the RG, if they are looking for a guitar that allows for a variety of timbres, they might opt for the SA or MW, but then they will not have such an intense volume as the RG. As a conclusion, the choice for an instrument will be due to a musical aesthetic sense on the part of the performer, who will seek his instrument privileging some characteristics to the detriment of others.

5. Conclusions

This work has addressed how to differentiate between high quality sound instruments and less quality sound instruments for the chosen instruments, which is a perceptual hearing, more or less, easy task for a qualified musician, and arduous to be performed by a computational system. However, even if the beauty of an instrument's sound is a subjective feature by the perceptual hearing of the musician, frequency spectrum has enough information to assess essential physical characteristics of a high-quality sound instrument.

Through experiments, the six specific instruments measured demonstrate, by means of their spectrum, the differences and similarities in frequency domain among high quality guitars and less quality guitars, with respect to the criteria defined here, based on, y mainly: on the intensity, density and frequency response.

As expected, due to different characteristic and thickness of the wood of, mainly, the top plate, the results show that the response for the high-quality instruments are consistent with the characteristics of the frequency response, as intensity, density, and range of the spectrum (color, timbre) that express sound projection, and that all together defines the quality of the instrument. For the instruments under consideration the named TKG1 show the less quality characteristics, in the middle range are the Di Giorgio Romeo 3 and Di Giorgio Master, in the high-quality instruments are the Martin Woodhouse followed by the Roberto Gomes, and Sérgio Abreu. It is important to emphasize that, among the high-quality classical guitars, it is not possible to define which has the best sound, due to the fact that high quality instruments are hearing perceptual defined, therefore, depends on the criteria of the musician. Therefore, the perceptual hearing of the musician is the best tool to define what is intended by a good instrument according to his own perception of how to interpret the music, but physical characteristics of the guitar are essential for a high-quality sound instrument and this is explicitly visualized in the spectrum. The criteria proposed here are necessary to have a good idea of the quality of the instrument, even for the non-specialized person in the area.

Future work is related to how to utilize this method to guide in the guitar construction by taking into account the thickness of the wood in the top plate, that defines the natural frequency response and progressively built instrument and measure the impulse response results, according to the criteria proposed here, in the intermediary steps of the construction, to give a good intuition of the final quality of the guitar.

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