BIOMECHANICAL SOUND SOURCE POLAR PATTERN MEASUREMENT

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Abstract –. *This papers presents a study of directivity of string instruments, in this case a charango. A comparison between different intensities is performed, generating both 3D and 2D polar patterns maps, using a developed matlab code. Systematic errors are taken into account in order to analyze the results. In this case, it was found that the instrument presents more directivity for high frequencies when the strings were strummed with more intensity. However, for low and mid range, the charango can be considered to present an omnidirectional energy distribution.*

INTRODUCTION

The purpose of studying the polar pattern of an instrument, in this case a string instrument, is to determine the distribution of energy generated by the source in the space, characterizing its energy distribution by angle and frequency.

There are 3D and 2D polar patterns, the 3D polar patterns provides more information than the 2D given the extra amount of angles studied.

In the present work, charango radiation patterns are analyzed for two different intensities: *piano* and *forte*, in order to determine its typical directivity.

The measurements are carried out with an angular resolution of 10º in the horizontal axis, with a frequency range from 20 to 20 KHz. Recordings are post-processed with a Matlab code specially developed for this analysis.

PREVIOUS STUDIES

A long time ago it was really difficult to study as source's polar pattern, more studies regarding the physical characteristics of an instrument can be found. Later on, with the advance in technology, information and the development of digital processes, the study of sound sources polar pattern became easier.

In 2010 Jukka Pätynen [1] uses a recording method using 22 condenser microphones situated in a dodecahedron shape in an anechoic chamber. Adding a microphone in front and another at the back of the source. Pätynen does an extensive analysis over various orchestra instruments, including string instruments.

On the other hand, in 2001 Felipe Otondo [2] carried out simultaneous recordings using 13 microphones with an angle variation of 45º.

BASIC TERMINOLOGY

Directivity

By measuring the sound pressure level at a constant distance from the instrument in different angles we can determine its directivity. This method is used for both 2D and 3D, the difference is the quantity of vertical positions analyzed. The results for each angle are band filtered to analyze for each third octave frequency band.

First of all it is required to define what is directivity, which will be a numerical figure that is calculated following the equation:

$$DI = 10\, log\, (Q) \tag{1}$$

Where Q, directivity factor, is obtained by the equation:

$$Q = \frac{4\pi}{\int_0^{\pi}\int_0^{2\pi}\left(\frac{p(\theta,\phi)}{p(0)}\right)^2 \sin(\theta)\, d\phi\, d\theta} \qquad (2)$$

In equation (2), if the denominator is equal to 4π the value of Q will be 1, which means that the source is omnidirectional for that frequency. Furthermore this equation establishes a relation between the acoustic pressure on the axis and the acoustic pressure at azimuth and polar angle.

TEST OBJECT

In the present work the instrument analyzed is a Charango shown in Figure 1, played by a charango session musician. The frequency of interest for this instrument starts at 300 Hz, this was determined by analyzing the Charango preliminary spectrum using an smartphone app previous to the main measurement.

The sound energy provided by the charango is determined by the resonating frequencies inside the body, which are generated by the vibrating strings.

The instrument is 65 cm long, 18 cm wide and 8 cm deep.

A charango has ten string and they are tuned according to the standard tuning for charangos which is shown in Table 1.

Table 1: Charango´s standard tuning.

String N°	Note	Frequency [Hz]
1st	E5	659.3
2nd	E5	659.3
3rd	A4	440
4th	A4	440
5th	E4	329.6
6th	E5	659.3
7th	C5	523.3
8th	C5	523.3
9th	G4	392
10th	G4	392

Figure 1: Charango used during the measurements

MEASUREMENT SETUP

Measurement Room

The measurement was carried out in an Auditorium which belongs to Universidad Nacional de Tres de Febrero, located at 4752 Valentín Gómez, Caseros, Buenos Aires, Argentina. Measurements took place on September 18th, in 2017, from 10 am to 6:30 pm. For this kind of measurements, an anechoic chamber would be ideal, however an auditorium was used in this case. The reverberation time at the stage is believed to be short when the curtains are closed, providing similar conditions to an anechoic chamber. For a more controlled measurement a real anechoic chamber is recommended, as reverberation times are usually below 100 ms, which is hard to achieve for normal rooms. Another reason for choosing the stage has to do with space: depending on the instrument being measured, the distance to microphones can become large.

The stage, which has a wooden floor and surrounding curtains, has a volume of approximately 450 m^3.

The auditorium is usually used for academic and artistic purposes such as conferences and music presentations.

The main idea is to avoid the reflections incoming from walls, roof and floor. The reflections from walls were easily covered because of the heavy curtains covering the sides of the stage. The stage curtain was closed so the stage was separated from the audience area, diminishing the background noise. The most problematic reflections were those coming from the floor. The effect of these reflections was intended to be controlled by filling the measurement area with absorption material in order to avoid direct reflections.

Equipment

The equipment used is described below:

- Anvil PROEL Forc3 Series FOABSR4U 19" (RME Fireface UFX+ and OctaMix)
- 16 Earthworks M50 Measurement Microphones.
- Sound Level Meter Svantek SVAN 959.
- SV 30A Class 1 Acoustic Calibrator.
- Outline ET250-3D Electronic Turntable.
- Laser BOSCH DLE 70.
- Audio-Technica ATH-M50x.
- Notebook SONY VAIO VPCEB2MOE

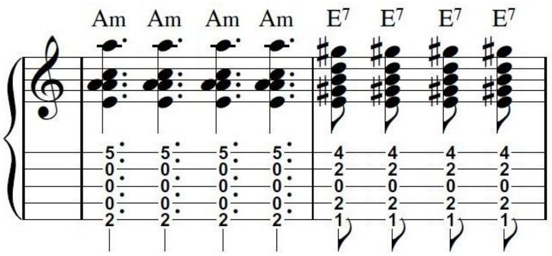
METHOD

Intensity

Two different intensities are tested, piano and forte. The first consists of 4 bars playing 2 chords, with gentle finger strumming and the second one consists of the same passage but with loud nail strumming. While more than 2 chords could have been used in 4 bars, by choosing 2, the repeating chord serves to decrease uncertainty levels.

The difference in loudness between intensities should be enough in order to find contrasting results. For this reason, previously to the measurement, the musician was told to rehearse both intensities using a smartphone app that showed the levels difference, moreover, it allowed to test its consistency. The smartphone was positioned in front of the musician throughout the entire measurement to assure a degree of consistency.

Musical Passage



Musical passage played by the musician

Figure 2: Musical passage selected

Musical passage shown in Figure 2 was selected in order to provide excitation for most of the frequency range that the instrument can produce. The lowest frequency (329.6 Hz) is generated by the 5th string played without plucking any frets, and many of the following lower frequencies are excited at the same time by using the Am chord. By playing the E7 chord, one of the highest notes in the charango is played, this is an A5 (881 Hz) that produces higher harmonics up to 10 KHz with a considerable amount of energy.

Besides the frequency range that it is achieved by these chords, they also allow the musician to play with a good degree of repeatability regarding the intensity between the *piano* and the *forte.*

Click Track

In order to assure timing consistency between chords, a click was used. It was set to 80 beats per minute as it allows to record the chord decay between each strumming. Even more so, the musician can change chords easier, avoiding spending time in possible retakes. By using the click, energy distribution in the recording is the same for every measurement. Another important advantage of the click track is that the measurement procedure becomes more organized as the musician knows when to play and how. Lastly, the final recordings are stacked in such a way that it allows for faster post processing later, which consists on cutting each measurement to the same length.

Calibration

Before measuring the instrument´s polar pattern it is needed to calibrate the equipment used, this means, recording a reference signal through each microphone attached with an XLR cable to its respective channel of the audio interface converters. For this step, SV 30A Class 1 calibrators are used. Its settings are configured to 94 dB SPL at 1 KHz. The gain in the Pre-amps was almost the same for each microphone with a difference not greater than 2 dB, this may be due to the different lengths and brands of the cables, and internal hardware differences between each channel. The calibration signals for the 16 microphones were recorded.

If this procedure is followed, resulting waveforms for each microphone should look similar to Figure 3. Waveform amplitude peaks below 20% of the distortion limits because charango´s levels are considerably lower than those used for 94dB microphone calibration. Strumming decay should be clearly seen. Each clip is cut to 6 seconds for post processing.

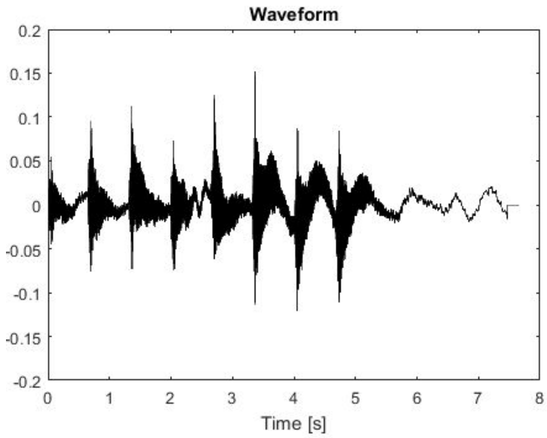


Figure 3: Sample of recorded waveform (degree = 0°, center microphone)

Reverberation Time

The next step is to obtain the room's reverberation times for every third-octave band. The method consists of exploding several balloons (9 in this case) in various positions (3 in this case). For each measurement, the full 16 microphones were used, which increased considerably the amount of data, therefore, decreasing the uncertainty of the measurements. Samples were post processed using Audacity Aurora´s Acoustical Parameters module in order to obtain the reverberation time.

Background Noise

Another parameter that needs to be calculated is the background noise, for this measurement the stage curtain is closed and the air conditioner off. The 16 microphones are used to measure the background noise, recording 30 seconds for each microphone.

Calibration is repeated to ensure the results have no error. To verify the measurement a Sound Level Meter Svantek SVAN 959 is used to measure the background noise to compare it with the results obtained.

After finishing this early measurements, microphone calibrations were done for a third time before the polar pattern recordings.

Reactive Field

In order to obtain reliable measurements, microphones have to be placed at such a distance that the reactive energy has the least amount of influence in the results. KR needs to be calculated.

The temperature conditions on the 18th of september were around 20° C between the moment when the measurements started and the moment when it finished. The resulting sound speed is 343 m/s, according to equation (3).

$$c = 331.4 + 0.61 \cdot T \quad (3)$$

Where C is the sound speed and T is the temperature in the auditorium that day.

With the sound speed parameter and the lowest frequency of interest established, the k.r was calculated following equation (4).

$$k \cdot r = \frac{2\pi}{c} f\, r \quad (4)$$

Where k is the wavenumber, r is the distance to the source, c the sound speed and f the lowest frequency been measured. By using this equation. distance between every microphone and the source can be determined. The optimal k.r chosen for this measurement was 5.76, due to the limitations in space regarding the microphones positions and especially the microphone positioned under the musician. The resulting radius of the semi sphere of the microphones array was calculated to be 1.15 meters.

Following the relationship between the active and reactive field in the air shown in Figure 4, the k.r chosen leads us to a 13% of reactive impedance at the distance r, where the microphones were placed.

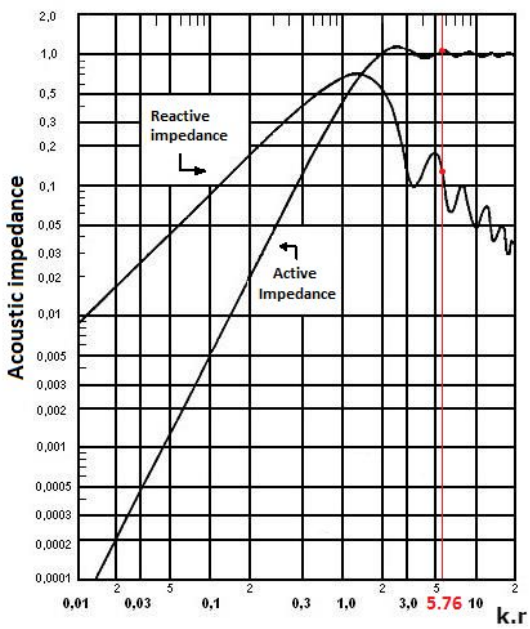


Figure 4: Relationship between Acoustic Impedance and k.r.

Microphone Arrangement

For the analysis of polar pattern 16 microphones were arranged in a semi-circle shape with an angle of 12.85 degrees between each of them as shown in Figure 4. This is done in order to obtain measurements at the very top and very bottom of the imaginary sphere, as well as having a central microphone measurement for 2D analysis.

Figure 4: Microphone array setup

The microphones were numerated from top to bottom, meaning microphone number 1 was located above the musicians head while microphone 15 was located near the floor surface. In this work a reference microphone was used to provide information about the intensity of each musical passage played, so the deviation produced by how the musician played could be compensated later when the audios were processed in Matlab.

To achieve a good reference measurement it was essential that the distance between the instrument and the reference microphone was the same along all the different degrees measurement. To obtain this fixed distance the reference microphone was placed by the musician's feet so it can rotate in the same way that the musician did.

Reference Microphone & Turntable

A reference microphone is needed in order to correct any level difference between each array of recordings. Ideally, the reference microphone should be positioned in such a way that allows the registration of variations in level for every frequency, However, it was not possible in this configuration to locate a reference microphone in front of the musician while guaranteeing location invariance throughout every measurement. Therefore, it was decided to attach the reference microphone to the turntable so its relative distance to the musician stays always the same for each measurement. Locating the reference microphone low relative to the instrument could imply bad strumming level corrections in post processing due to the instrument's body causing interference for some frequencies.

Both the musician and the instrument were standing over a turntable that rotates a precise amount of degrees in a controlled way. Turntable was configured to change angles by 10º increments, manually controlled.

In the end, because two different intensities were tested (piano and forte), 1152 audio files were recorded. In order to process the audio files obtained it was essential that all the files have the same length, so every file was edited so they can be loaded into Matlab code for processing.

Post Processing

After measurements are recorded, every clip audio is cut to length and named according to its degree and microphone position. The clips of a particular intensity as well as their corresponding microphone calibrations are loaded into a matlab code which calibrates the signal in order to obtain a validated sound pressure level. Each audio sample is filtered into third octave bands and compiled into a matrix which it is used in order to apply a reference correction level. Once every measurement is calibrated, filtered and corrected, different plotting codes are developed in order to analyze the results. Once the matlab code works, it is put together into a user friendly interface. The user can load its data and obtain results after the computer is done processing, such time was recorded to be 15 minutes for this case. The code developed is able to show 3D and 2D polar patterns as well as sonograms and Q values for every third octave band.

RESULTS AND DISCUSSION

Background Noise

It was critical to determine the background noise in thirds of octave in the chamber at the moment of the measurement to assure the condition that at all times the lowest sound recorded is 10 dB above the background noise at least. This is because with differences larger than 10 dB, the influence of noise levels are less problematic.

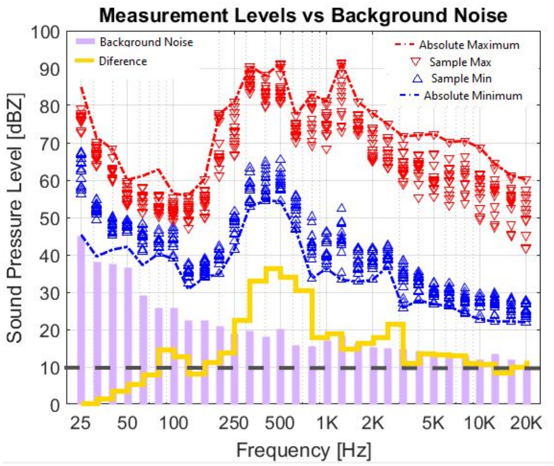


Figure 6: Background Noise Results

Figure 6 shows maximum and minimum recorded levels for every measurement. From this data, maximum and minimum curves can be traced. This is done in red and blue colours respectively. Later on, the minimum curve can be compared to the background noise levels to obtain the minimum absolute difference for the entire measurement in each third octave band, shown with the yellow stroke. As it can be observed, this difference is always above 10 dB in the frequency range of interest, which is above 300 Hz. However, this is not the case for the 16 KHz band, which is barely below. Since this curve only shows relationships to the minimum values, the vast majority of the measurements are validated to be well over 10 dB above the background noise level, more than 70 dB in some cases. Having this relationship established it allows the results of the measurement to be properly analyzed.

Reverberation Time

Figure 7 shows the results for the reverberation time. As it’s shown the average RT [2] value is 0.34, with a higher value in lower frequencies, then a decrease in 800 Hz, a tiny increase by 3000 Hz and finally a decrease with the increase of frequency.

It is hard to achieve short RT to imitate what should happen in free field conditions, but for the frequency range of interest, in this case an RT of 0.34 seconds implies that the sound field is far from diffused, and energy levels are consequence of the instruments acoustic radiation in a greater degree than the room´s response.

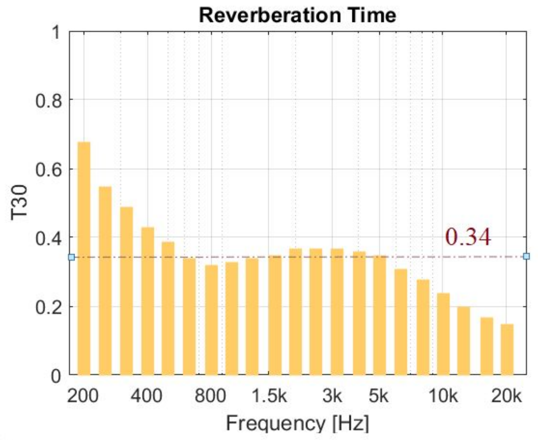


Figure 7: Reverberation time results by third octave bands.

Frequency Response

Two different playing intensities were studied in this work, it is interesting to analyze what happens with the frequency response when the same instrument is excited in dissimilar ways.

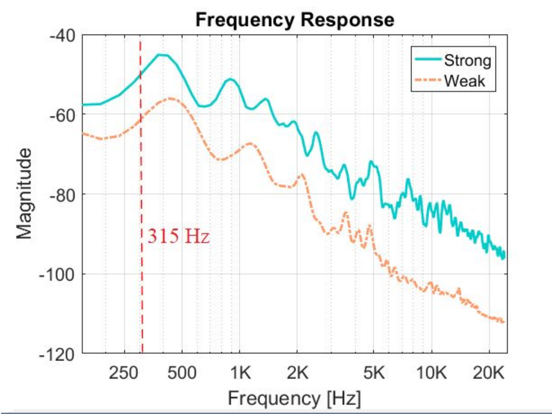


Figure 8: Frequency response for different intensities.

In figure 8 it can be appreciated how the main lobes are centered in quite different frequencies. For the strong intensity the main lobe is around 400 Hz and in the *piano* intensity the main lobe center is closer to 500 Hz. Another important information that can be extracted from this comparison is that when the charango is excited with more strength like in the *forte* passage more harmonics appear, especially the odd ones. It can be seen that there are more secondary lobes in the *forte* intensity than in the *piano* sequence which means greater even harmonic presence when the instrument it is played harder.

3D Polar Pattern

Since 3D polar pattern plots are graphed for each third octave frequency band, a total amount of 30 plots can be obtained from a single analysis. Besides the particular results used for analysis in this paper, the rest is shown as images in a annexed folder. It is also included a GIF image for each intensity.

The most important bands to analyze first are the fundamental ones. The results for the band of 315 Hz in the forte passage which is the starting frequency of importance, is shown in figure 9.

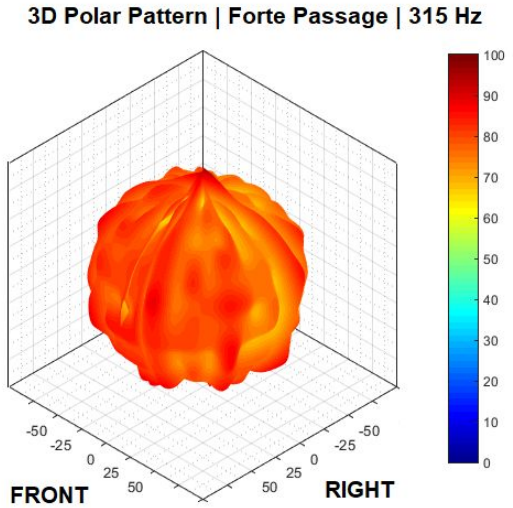


Figure 9: 3D Polar pattern, forte, 315 Hz

It can be observed that the energy distribution for this frequency range is homogeneous for the most part, with greater levels at the front and lower levels at the back of the instrument. Some degrees show more intensity than others, but in a mostly random way. This is true for the piano passage also, as shown in Figure 10.

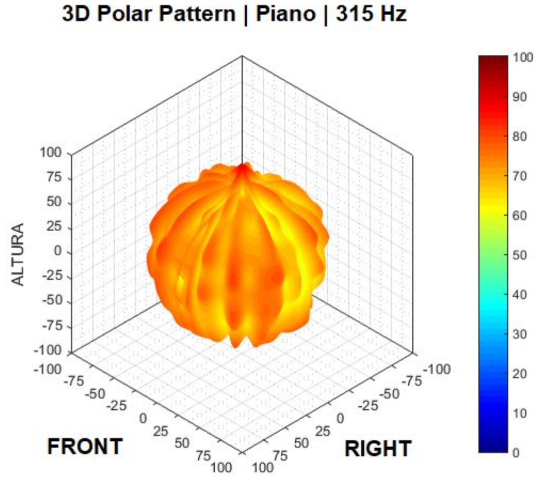


Figure 10: *3D Polar pattern, piano, 315 Hz*

Another interesting frequency band to analyze is 1250 Hz, because some strange strong spikes are present for forte passage whereas in the piano passage are not. This spikes can be associated with a resonance of the string at this frequency, given it is the 4th harmonic band. Resonance levels can be unpredictable and direction dependent. A symmetry can be found comparing both sides of the sphere.

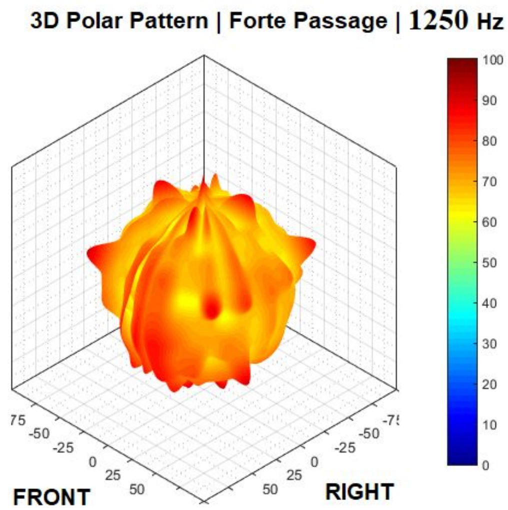


Figure 11: *3D Polar pattern, forte, 1250 Hz*

The piano passage shows overall less intensity for all degrees, while conserving the strong passage tendency for directivity. Most energy resides in the front and energy at the back starts to reduce.

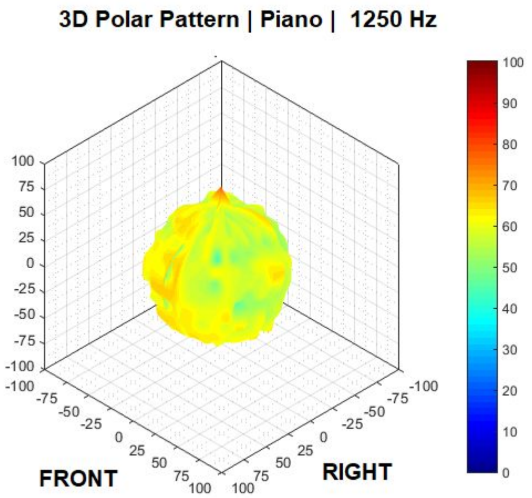


Figure 12: *3D Polar pattern, piano, 1250 Hz*

Once analyzed low and medium frequency range, it is time to see how the instrument directivity response behaves for high frequencies, shown in Figure 13 and 14. For intensities, overall levels are considerably reduced in all directions. Directivity in the central angle is sharply increased for forte intensity, showing an asymmetrical pattern for the right side. This may be related to the way the instrument is held. The left side is mostly blocked by the strumming arm, while the right is free and shows more intensity. Similar radiation can be observed for the meridional angles, but with less intensity for the bottom side.

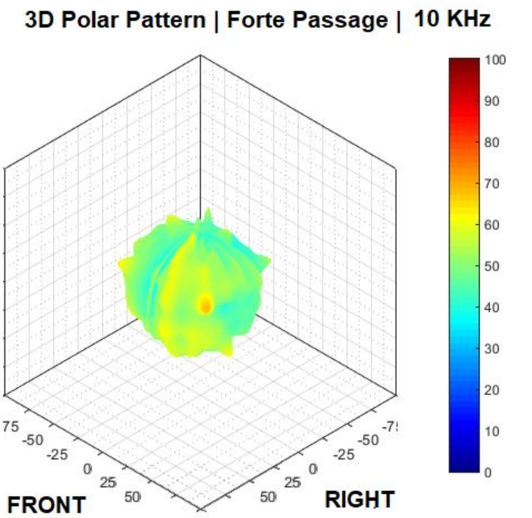


Figure 13: *3D Polar pattern, forte, 10 KHz*

Piano intensities show considerably less directivity for high frequencies compared to the forte. Its level shows rapid diminution as it reduces close to the global background noise level, but still 10 dB over its respective band noise level.

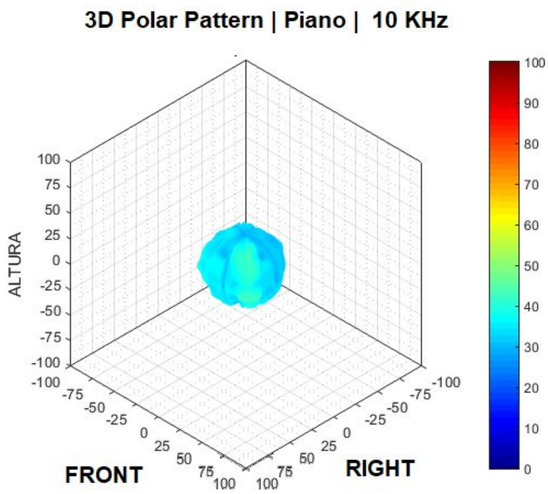


Figure 14: *3D Polar pattern, piano, 10 KHz*

2D Polar Pattern

2D Polar Patterns are obtained for 3 different axes. The equatorial, the frontal meridional (which is the circle associated with 0° and 180° angles), and the lateral meridian (which is the circle associated with 90° and 270° angles).

Similar to the 3D analysis, the fundamental frequency related to the 315 Hz band shown in Figure 15 is inspected, which shows the piano passage.

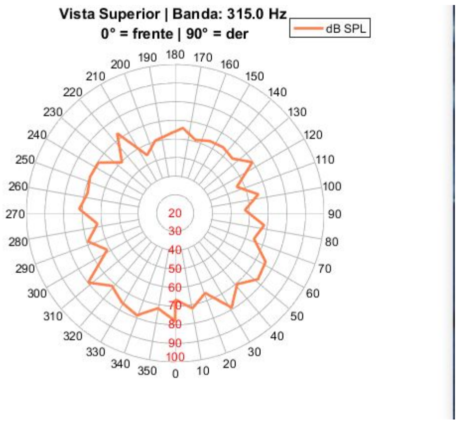


Figure 15: Polar pattern, piano passage, 315 Hz.

From this equatorial view, it can be seen that differences with amplitudes of more than 10 dB appear between two neighbour angles. This discontinuities may be related to the reactive behaviour at frequency. Which may indicate that the value of k.r used for this measurement should have been higher. Another possible cause may be related to the acoustic resonance of the instrument, given its fundamental frequency which belongs in this range. Despite, energy concentration is still 20 dB larger in the front than in the back.

Similar response is observed in the respective forte passage. Most lateral and frontal polar patterns could be considered omnidirectional for frequencies below 5 KHz. Figure 16 Shows how front intensities became larger compared to those in the back at 8 KHz for the forte passage in a lateral view. On the other hand, piano passages directivity is comparably more homogenous for the rest of the frequencies.

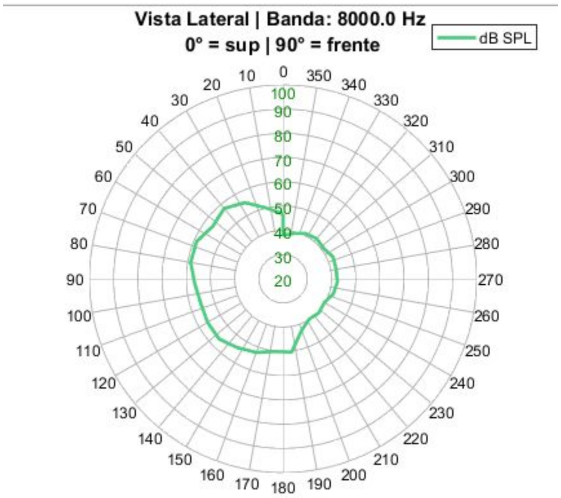


Figure 16: Polar pattern, piano passage, 8 KHz.

Finally, at very high frequencies, the instruments directivity at forte passage is very high, as shown in Figure 17.

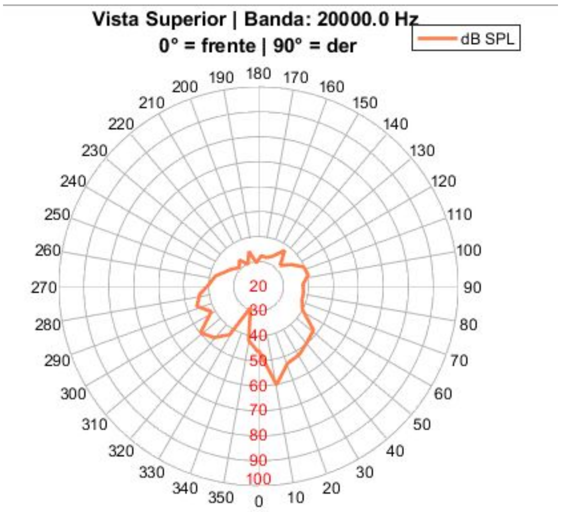


Figure 17: Polar pattern, piano passage, 8 KHz.

It can be easily observed that the front has 60 dB peaks while the back levels are close to background noise levels. An asymmetrical distribution of energy is also observed for the right hand side as opposed to the left hand side, also seen in the 3D plot before.

In general thoughts, there is a difference regarding the decay of the amplitude when comparing the piano and forte passage for every angle. The piano passage decays more quickly with frequency than forte passages.
Another difference between the two intensities is the distribution of energy, in the piano passage the energy is distributed more equally but in the forte passage the radiation is mainly frontal, so the result will be that the directivity and radiation of energy of the Charango varies with the intensity in which the instrument is played.

Directivity Coefficient
By analysing the data coming from the same axis than those used for the 2D polar pattern plots, a Q factor graph can be obtained, such as it shows the behaviour of the axis directivity for each frequency. Results for forte and piano intensities are shown in Figure 18 and Figure 19 respectively.

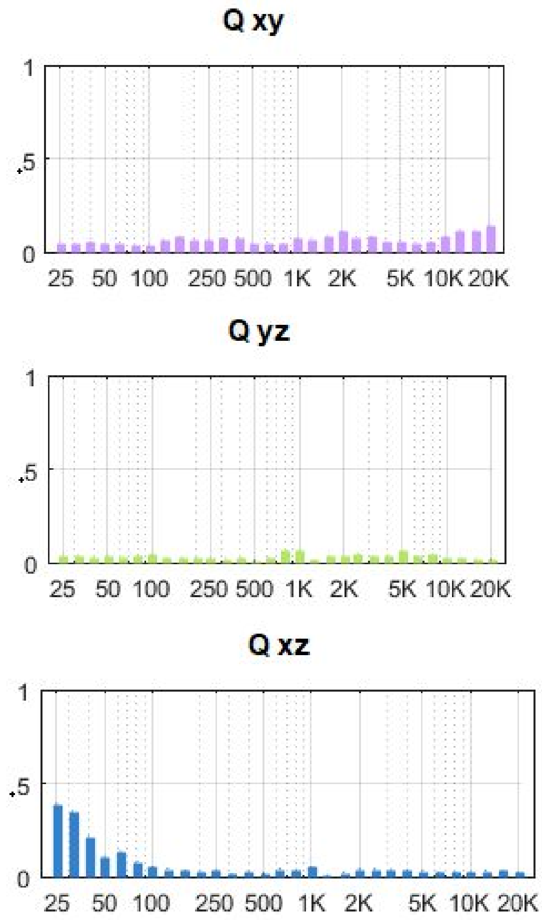


Figure 18: Q factor for every frequency. Equatorial view(top), Meridional 0-180 View (Mmd), Meridional 90-270 View (bottom), forte.

It is important to consider that results under 300 Hz must not be considered as the instrument do not provide energy below this frequency. Apart from that, it can be seen in the Qxy graphic that the charango gets more directional as the frequency increase. This is consistent with the results obtained analyzing the polar pattern plots. The Qyz plot shows that energy for the 0° and 180° is bigger for 1 KHz and 5kHz bands. The Qzx plot shows a strong increase in low frequencies in the lateral angles, that can be correlated to a side low hum, possibly associated with plumbing noise.

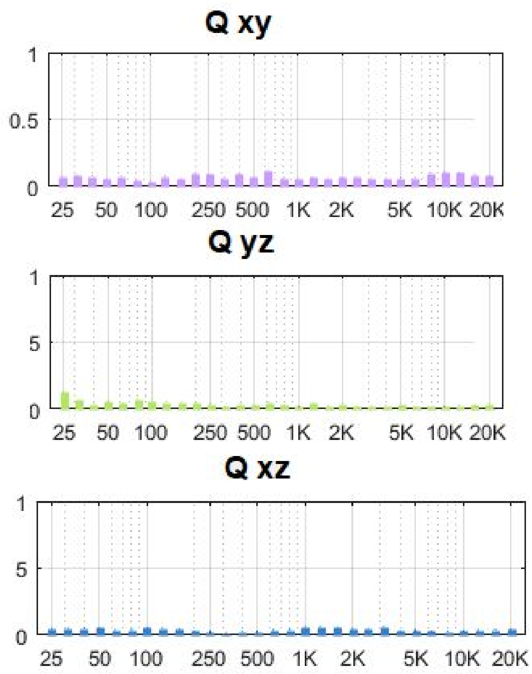


Figure 19: Q factor for every frequency. Equatorial view(top), Meridional 0-180 View (Mmd), Meridional 90-270 View (bottom), piano.

On the other hand, the intensities for the piano passage does not show the same correlation of directivity to frequency than the forte. In this case, it is most concentrated in the midrange and top end in a discrete way, rather than a monotone increasing curve. Results for meridian directivity can be considered somehow similar, implying a omnidirectional pattern in those planes.

Sonogram

By compiling every sound pressure level associated to an angle and a degree, a more detailed map can be constructed. A sonogram maps every measurement to a surface that can easily show directivity over frequency. Results can be found in Figure 20 and 21 for the piano and forte intensities.

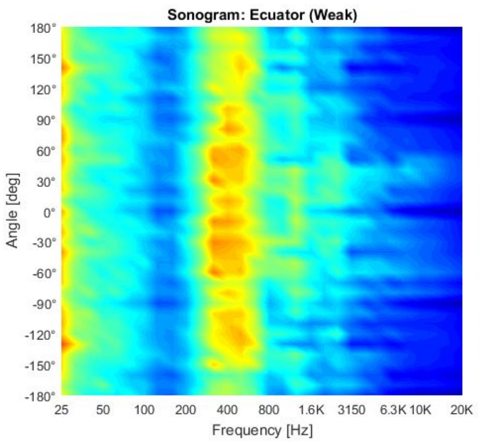


Figure 20: Sonogram: equatorial view (piano intensity).

As it's explained in previous works, strings instruments tend to be omnidireccional in lower frequencies, the charango is not an exception. After analysing the results, it was concluded that most of the energy radiated from the instrument when it is played softly is somehow omnidirectional in its main frequency range. It can be seen that only angles close to 0° have levels above 50 dB in high frequencies. The main focus of energy corresponds to 400 Hz band as it contains the fundamentals of each chord. Below 200 Hz the instrument has no radiation of energy at all. For frequencies below 50Hz it can be found a considerable amount of energy associated to low frequency noise. Three main lobes can be visualized at 315, 1250 and 2000 Hz bands, which corresponds with multiples of the fundamental frequency.

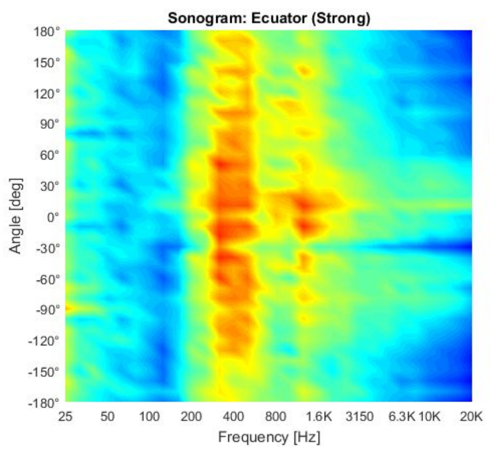


Figure 21: Sonogram equatorial view (forte intensity).

By analysing Figure 21, it can be seen that sound directivity is increased for higher frequencies. Angles close to 0° show up to 20 dB difference to those at 180° for the fundamental range. This difference grows up to 40 dB for frequencies larger than 5 KHz.

To analyze the difference in directivity between both playing intensities another sonogram was can be made, but this time showing only the differences in directivity. For such analysis, weak intensities must be matched to those of the strong passage. In order to do this, spherical rms was compared and later, the normalized correction was applied.
Results can be observed in Figure 22.

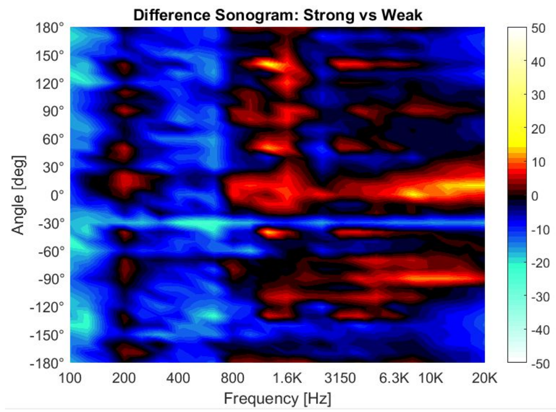


Figure 22: Difference sonogram: strong vs weak.

Black colors show the degrees and frequencies for which the intensity is invariant to the directivity. Red to Yellow colours show the degrees and frequencies for which the strong passage is comparably louder than the soft passage. On the other hand, blue to light blue colors show values for which the weak passage is comparatively louder than the strong passage.
At a first glance, it can be confirmed that strong passage is considerably louder than the weak passage for high frequencies, not only in the 0° angle, but also for discrete angles such as the sides, although not symmetrically.
Figure clearly shows how the main energy difference is placed in higher frequencies, especially starting at 1.6 KHz. Another big difference can be spotted at 3.2 KHz, which means that harmonics are being excited in the forte passage that in the weak passage are not.
Interestingly, there is a noticeably strong beam at -30° that is somehow constant for all frequencies.

This is associated to the musicians arm position which served as an acoustic shadow, blocking the instrument radiation as previously analyzed. Meridian sonograms and comparisons images can be found in the annexed folder.

CONCLUSIONS

As a conclusion, the measurement of polar pattern of a charango was carried out successfully. The behaviour of the sound source (charango) is obtained and analyzed for different frequencies and also for two different intensities.

Results show that maximum levels were recorded for frontal angles rather than rear for the entire frequency range for both intensities, presenting a somewhat omnidirectional pattern for low frequencies. The maximum amplitude for polar pattern is at 1250 Hz irradiating most of its energy to the front, and then to the sides and the back it is mostly equally distributed. The amplitude of the polar pattern starts to diminish considerably at 3150 Hz.

Harmonic relationships can be found between each lobe present in the directivity maps, mostly even.

Forte passage resulted to present more directivity for higher frequencies than those of the Piano passage, quite significantly as shown by the difference map. By in large, this results confirm the theory that for string instruments, the directivity pattern changes depending on the intensity in which the strings are strummed.

In a more general view, this kind of measurement is considered to be quite expensive, considering the needed for 16 microphones, that in this case were class 1. Lower resolution results can be seemingly obtained by reducing the amount of microphones.

An anechoic chamber is essential for this kind of measurements, as sound pressure level recorded in each microphone position should be related to the source and not the room. The auditorium stage used in this case allowed the measurement intended. Rooms with larger reverberation times could end in erroneous results. Last but not least, the KR value used for the arrangement of the microphones is essential in order to obtain valuable information of the instrument low frequency response. A slightly low KR value used in this case may have been the reason for inconsistency in results for bands below 300 Hz, which is slightly below the instrument's lowest frequency of interest.

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