BIOMECHANICAL SOUNDSOURCE POLAR PATTERN MEASUREMENT OF A CAVAQUINHO

FREIDKES, JONATHAN [1] MANTECA, JOAQUIN [2] AND VISKOVIC, MANUEL [3]

[1] Universidad Nacional de Tres de Febrero, Caseros, Argentina.
jonifreidkes@gmail.com
[2] Universidad Nacional de Tres de Febrero, Caseros, Argentina.
mantecajoaquin@gmail.com
[3] Universidad Nacional de Tres de Febrero, Caseros, Argentina.
viskovicmanuel@gmail.com

Abstract – *This paper presents a study of directivity of string instrument, particularly a cavaquinho. 3D and 2D polar patterns and sonograms are obtained. The analysis is based on two different intensities and two different ways of exciting the strings, with hand and pick. All possible error sources are considered and explain how it affects the expected results. Is found that polar pattern is not a constant and cannot be observed only in function of frequency as is usually done. Dynamics and played tone are also an influence on the variability of directivity.*

1. INTRODUCTION

The studies of musical instruments have a lot of orientations at science. The physics of string instruments has been studied in order to understand its development and how timber can be evolved by luthiers or professional players [1]. Frequency response, loudness, harmonic content, ease of response, directivity and many others can be studied [2]. This paper focus on the directivity measurement and its development at imperfect conditions.

Directivity has not been an important issue for research until Meyer's investigation [3]. He analyzed different seating arrangement and how this affects to different concert halls and type of compositions. He emphasizes that sound directivity is crucial for acoustics situations where the energy of the instrument and the room is compromised.

Another focalization for directivity is auralization and acoustic modeling, in this subject Lokki [4] made his investigation. That work affirms that directivity on a spherical surface is a function of frequency, played tone and dynamics. Intensity for dynamic variations will be *Piano* and *Forte*.

Otondo and Rindel [5] investigated the directivity in order to verificate the direct influence on the sound field created in the room according to acoustical parameters. They obtained good results by averaging three random tones as music passage.

According to previous works the challenge is to generate a graphic representation that allows to understand better and easier the directivity of an instrument. The objective is to design a microphone arrangement for polar pattern measure and make a Matlab software that generates a 3D representation.

In this investigation, the analysis is done for a cavaquinho, measured in three axes with ten-degree resolution. The procedure will be explained, and then the implementation and its results will be showed.

2. THEORETICAL BACKGROUND

Adapting Beranek's definition the polar pattern is a description of an instrument response in function of the direction of the transmitted wave in a determined angle and frequency [6]. The points of measurement for this description should be in a specific distance that needs to be exactly the same to all angles. So is important to define that distance and how it will be found. First of all, it is necessary to define the concept of critical distance. This is the point at space where the direct field becomes reverberant field [7]. Equation 1 define how to calculate the critical distance so a sphere of direct sound can be estimated. Q factor is consider 1,. assuming that the propagation is spherical according to the measure that will be necessary done in all directions.

$$Cd = 0{,}06\sqrt{\frac{V}{RT}} \text{ (Eq. 1)}$$

Where V is the volume in m^3 and RT is the reverberation time (RT60).

Having an appropriated development of waves is essential to study polar pattern. An anechoic space is needed to avoid room reflections and ensure that the measurement is done only from the source direct sound. In this case, the Universidad de Tres de Febrero auditorium stage will be adapted so that the conditions are similar to a semi-anechoic chamber.

It is necessary to define the conditions where reactive field ends, this can be analysed under Beranek studies. Equation 3 shows that distance to be considered depends on wavelength interaction. As lower the frequency of analysis further the measure point should be from the source.

$$k = \frac{2\pi f}{c} \quad \text{(Eq. 2)}$$

$$Z = R + j\,X = \frac{(kr)^2 \rho c}{(kr)^2+1} + \frac{kr\rho c}{(kr)^2+1} \quad \text{(Eq. 3)}$$

At figure 1 it can be observed that when kr term is equal to 1,0 the active impedance starts to be equal than reactive, so as far as the measure is from this point more stable is the field. It will be considered that a value larger than 5 will be enough to consider that the measurement point is at the resistive field, according to Beranek's *'Acoustic'* analysis of sound radiation.

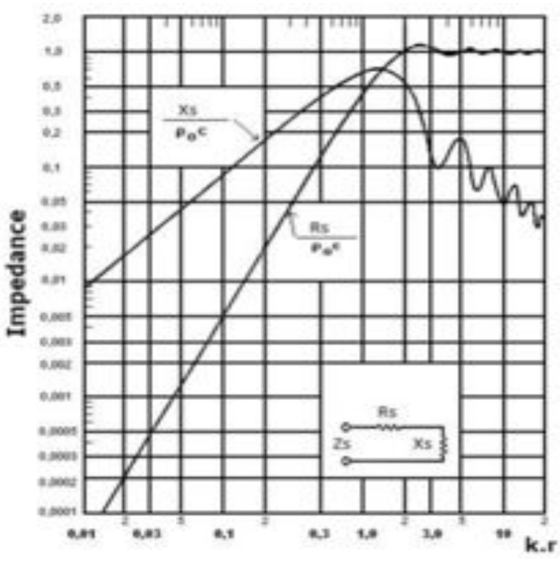

Figure 1 Specific acoustic impedance normalized of the air charge.

Conditions mentioned will define the far field when impedance is mainly active; so that we can assume that the inverse square law is effective. In this case the wave propagates as spherical.

3. MEASUREMENT PROCEDURE

3.1 INSTRUMENT

The cavaquinho is a Portuguese instrument inherited by Brazilians. It has four metal strings and a high registration. In this case tuning is D, B, G and D. So the lowest note of interest is D. There is an analysis of which frequencies contain this D in section 3.2.

Figure 2. Brazilian cavaquinho

3.2 MUSIC PASSAGE

The selection of the music passage is based on the tonal characteristics of the instrument. It is necessary to be consider that the instrument have metal strings in tiny dimensions so higher harmonics are present as part of the characteristic timber of cavaquinho. To verificate this, a previous spectrum analysis were obtained from other similar cavaquinho recording.

Looking at figure 3, the spectrum shows that the lower string, D note, has the fundamental in 280 Hz and harmonics appear up to 5 kHz. Playing chords on cavaquinhos will be more comprehensive of the instrument considering post processing limitations.

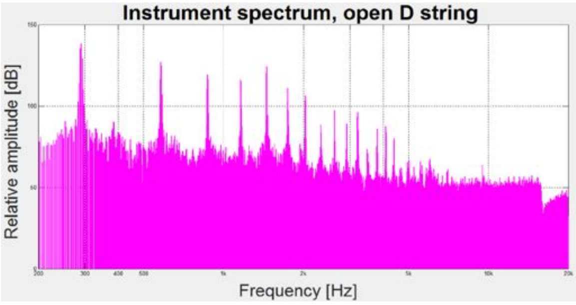

Figure 3. Preliminary analysis of spectrum[1]

According to this preliminary analysis we obtain that lower frequency of interest is 280 Hz, so the first third-octave-band for analysis on this paper is 250 Hz. In order to this frequency is possible to calculate the *kr* term of equation 3.

Under the explanation and analysis a music passage need to be decide and prepare. The capability of reproducibility of the program is essential to have coherent. So, taking in count Lokki's work frequency, played tone and dynamics need to be studie. Music sheet at figure 4 be played in two different intensities, *Piano* and *Forte* (Figures 5 and 6). Where, also, the Piano intensity is played with hand and Forte, with a pick. This type of execution is made in order to been abarcative to the sound characteristics of the instrument.
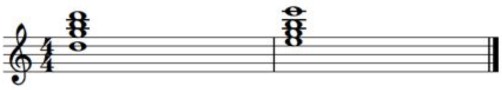
Figure 4. Music sheet for music passage

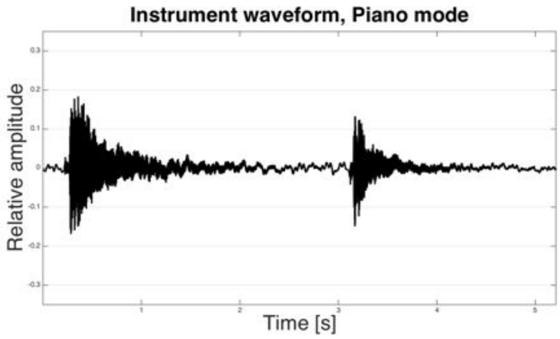

Figure 5. Instrument waveform *Piano*

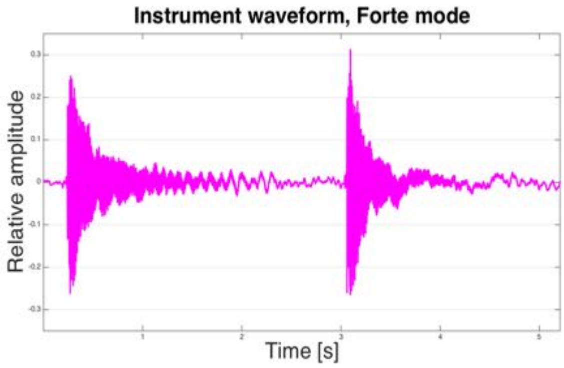

Figure 6. Instrument waveform *Forte*

These two notes are processed together for the 2D and 3D polar pattern in each position.

3.3 MEASUREMENT INSTRUMENTATION

- 16 Microphones Earthworks M50
- 16 KRV microphone stands
- 16 XLR cables
- 1 Svantek SV-30-A calibrator
- 1 omnidirectional source Dodecahedron
- 1 Audio interface RME Fireface UFX+ with 16 inputs via adat protocol
- 1 Svantek SVAN 959 sonometer
- 1 Outline ET230-3D turntable
- 1 MacBook Pro

3.4 MEASUREMENT CONDITIONS and PREVIOUS CALCULATIONS

As it has been explained before, the measurement take place on Universidad de Tres de Febrero auditorium situated on Valentín Gómez

[1] In order to have a better appreciation the figure is present in annex C.

4772, Caseros, Buenos Aires, Argentina. Specifically, on the auditorium stage, with his curtains down at front and back of the stage.

For this measurement, it is necessary an anechoic room to avoid the reflections and be sure that the sound picked up by microphones come from the direct sound of the instrument. On this way, a reverberation time measurement has been made to determine if the auditorium stage has the conditions necessary to consider the results as useful.

In order to measure the reverberation time, a Dodecahedron has been hanged up in the middle of the stage as it is shown in figure 4. The technology of this source only allow the measurement to be accurate above 250 Hz due to the absence of a complementary subwoofer for the Dodecahedron.

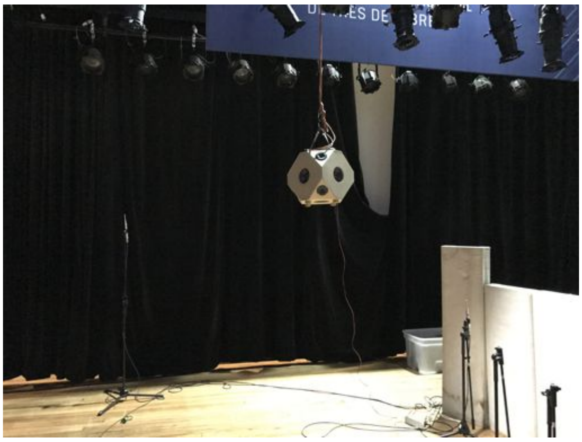

Figure 7. Reverberation time set up measurement.

Then, 6 microphones are placed with at least 1 m distance to any surface of the stage, according to ISO 3382 [8]. Results for this measure attach to this standard by presenting results in bands of octave.

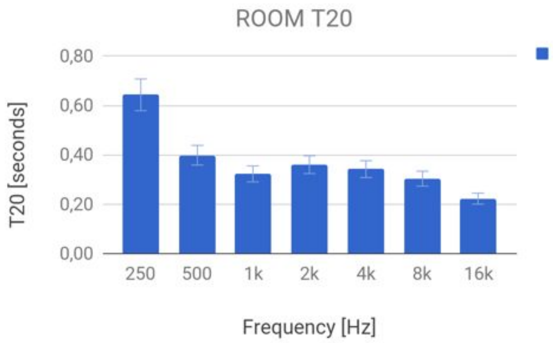

Figure 8. Room T20 from 250 to 16k (octave bands of interest) according to ISO 3382, with the deviation.

In order to have a better analysis of the acoustic room measure the results are present for frequency over 250 Hz. Values for lower frequencies are not in the band of interest.

Closing the curtains on the stage the enclosure becomes a shoe-box type with a length of 10 m. by 5.7 m wide and 8.2 m of height. According to these values the volume is 467.4 m^3. With these values critical distance may be calculated according to equation 1. It is expected that reverberation time has higher values for lower frequencies, as it sees in figure 8. So is accurate to evaluate the critical distance at the lower frequency of interest, as the worst possible case to consider for measure.

Cd [at 250Hz] = 1.62 m (±0.1m)

Critical distance calculation drags uncertainty from reverberation time measure. Measure should be at shorter distance that calculated for 250 Hz.

Background noise is measured at 6 different positions in one-minute recording and then averaged. Then, we are going to compare this values with the level sound of the instrument and obtain the frequency range where the difference between them is acceptable (over 15 dB).

3.5 MEASUREMENT ARRANGEMENT

A semi-circular microphone array consisting of 15 omnidirectional Earthworks microphones is hung up vertically as is shown in figure 7. The angle between one microphone position and another is 12,85° from the centre of the instrument radiation.

For this implementation previous calculus should be use. The radius of the arrangement should satisfy three conditions at the same time. The distance of 1,4 m from the floor microphone (EW 15 in figure 7) to the acoustic centre of the instrument, considering that the musician is stand up and over the turntable. In second place this distance should be under the calculated critical distance of 1,62 m and the *kr* term analysed before at equation 3 needs to be larger than 5. According to these conditions optimum radius is 1.4m and the k.r term has a value of 6,4.

The calculus of this conditions are in the Annex B.

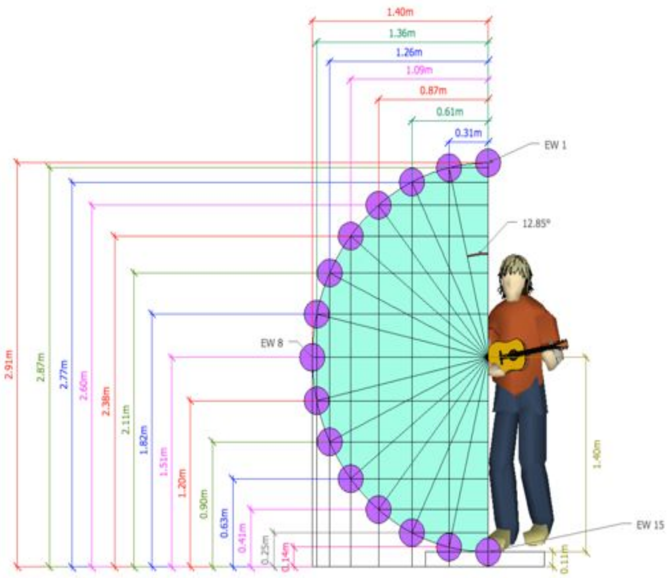

Figure 9. Disposition of the microphones arrangement[2]

[2] In order to have a better appreciation the figure is present in annex C.

In order to obtain the 3D polar pattern, the musician needs to be rotated 360 degrees. That rotation is done with a 10 degrees precision, from 0 to 350 degrees. Where 0 degree is when musician es place in front of the semi-circular arrangement.

In order to normalize the intensity of the musician in each angle, the level pressure of the microphone EW 1 in 0 degree has been taken as reference. Then, the difference between this measurement and EW 1 on other angle is calculated and then added to all the microphones on this angle. Same for all angles.

Figure 10 shows the semi-circular arrangement set up with the musician in the measurement position.

Figure 10. The arrangement implementation in situ.

It could be seen in figure 8 that the stand's height does not allow us measure without some desks to achieve the highest positions of microphones and that furniture introduce some errors because they have reflective surfaces. Also, the microphones pick up the floor reflection although we place an absorbent material to minimize that reflection effect and avoid comb filter effects.

The 15 microphones enter to the RME Fireface and then calibrated with the Svantek calibrator for 94 db SPL at 1 kHz.

4 MATLAB SOFTWARE IMPLEMENTATION

The designed Matlab script needs the measurement to be done in a similar way to the one described on this paper. This means, there should be the same microphone arrangement and equivalent turntable steps in order to work properly and export accurate results. The audio files also need to be renamed as asked: "MIC #_deg-mode.wav" (i.e. EW 5_130-02.wav for mic number 5 in 130° position, piano mode; or '-01' in forte mode). This is needed in order to load the audio files as a list containing specific positions meant to allow the code to index correctly each file from the array. Once the 1080 (15 microphones, 36 steps, 2 modes) audio files are loaded in the script, the calibration information is needed with a simple file name: "MIC #_CAL.wav" (i.e. EW 9_CAL.wav will be the calibration file for the ninth microphone). There is also an editable text to specify the average file duration in order to crop all files to the same length (4.5 seconds as default). Then, a complete signal process is performed once the 'Calibrate' button is pressed: calibrate to Pascal units, signal filtering in third-octave ANSI filters, transform to dB units and two 3D matrix are created, both 15x30x36 (15 microphones, 30 third-octave band, 36 steps), one for each playing mode, forte or piano. After that, the user should select the desired mode in radial buttons (forte as default) and later a central frequency to plot in 3D and 2D (in X=0, Y=0 and Z=0 positions). Once the plots are shown, the user may select the button to export the data to a standardised .xls spreadsheet indicating the selected mode and the frequency next to the whole SPL information.

5 RESULTS AND ANALYSIS

First of all, is important to know the useful frequency range according to the comparison between the background noise and the sound pressure level of the cavaquinho in piano intensity (the worst condition), picked up by central microphone (EW 8 in figure 7) at same height of the acoustic centre of the instrument and 0 degrees of the turntable.

The results of this comparison are below in figure 11 and table 1.

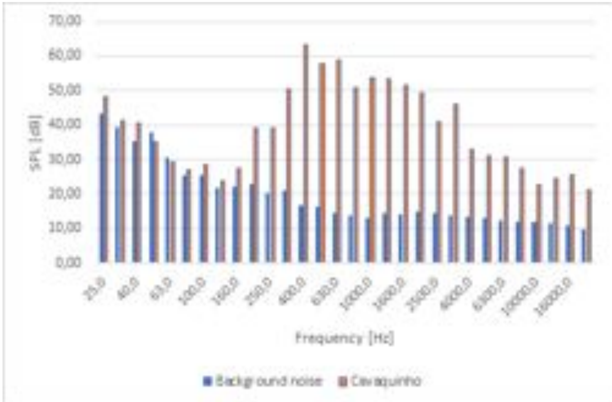

Figure 11. Level pressure comparison between background noise and the instrument in piano intensity.

Frequency [Hz]	Background noise [dB]	Cavaquinho [dB]	Delta
25	43,31	48,34	5,03
31,5	39,45	41,46	2,01
40	35,49	40,52	5,03
50	37,92	35,01	-2,92
63	30,74	29,34	-1,40
80	25,42	27,08	1,66
100	25,29	28,51	3,22
125	21,95	23,68	1,73
160	22,15	27,52	5,37
200	22,73	39,15	16,42
250	20,34	39,17	18,84
315	21,03	50,52	29,49
400	16,70	63,23	46,54
500	16,39	57,62	41,24
630	14,37	58,76	44,40
800	13,61	50,88	37,27
1000	13,21	53,60	40,39
1250	14,58	53,35	38,77
1600	14,02	51,43	37,41
2000	14,78	49,54	34,76
2500	14,64	41,02	26,39
3150	13,81	46,09	32,27
4000	13,34	32,87	19,53
5000	12,96	31,15	18,19
6300	12,43	30,82	18,39
8000	11,92	27,58	15,66
10000	11,76	22,70	10,94
12500	11,57	24,66	13,09
16000	10,87	25,81	14,94
20000	9,74	21,42	11,68

Table 1. Difference between instrument in piano intensity and background noise in dB SPL.

It could be seen that the difference is over 15 dB from 200 Hz to 8 kHz. So, we could analyse on this range, according to the measurement conditions.

However, we choose 400, 1000 and 5000 Hz to make the analysis. The first one because it contains the highest peak due to the summary of the fundamental of the two notes processed, as it could be seen in figure 12. The 1000 and 5000 frequency third-octave-band are selected to analyse mid and high frequencies.

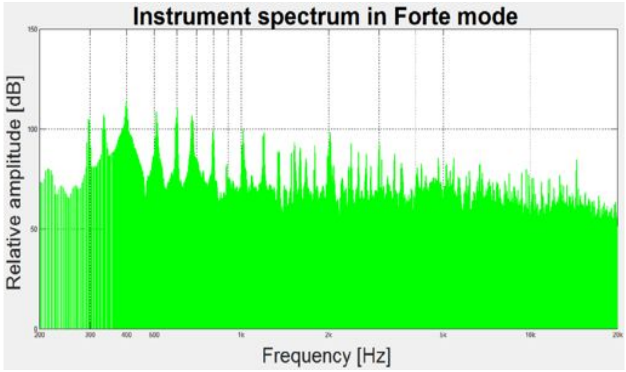

Figure 12. Continuum spectrum of analysed signal in Forte mode measure in 0 degrees with EW 8.[3]

Figures 13 to 18 display 3D polar pattern for that 3 third-octave-band frequencies for both intensities piano and forte, where 0 in axe Y is the position of the musician in front of the arrangement (0 degrees).

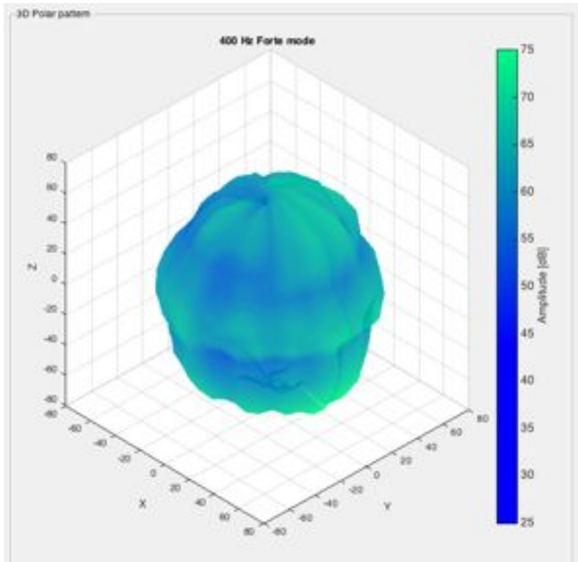

Figure 13. 3D polar pattern 400 Hz in Forte mode.

[3] In order to have a better appreciation the figure is present in annex C.

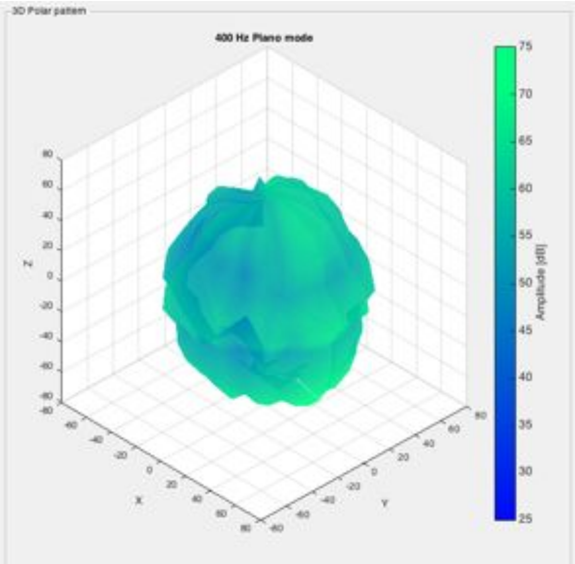

Figure 14. 3D polar pattern 400 Hz in Piano mode.

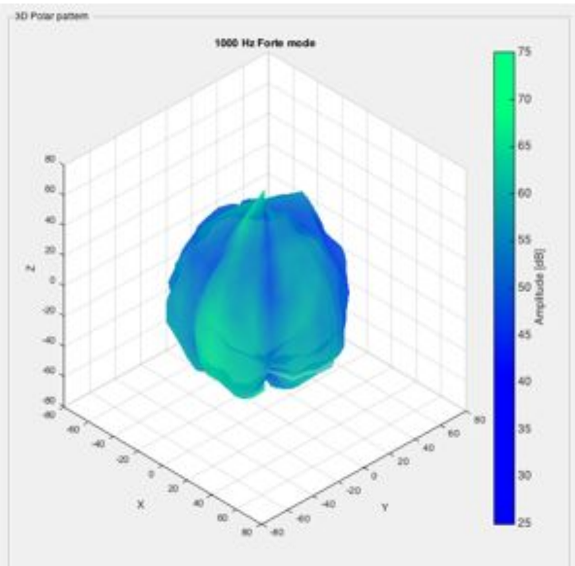

Figure 15. 3D polar pattern 1000 Hz in Forte mode.

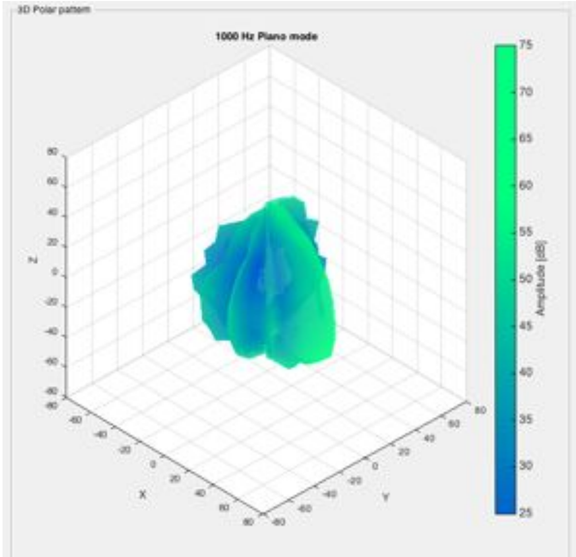

Figure 16. 3D polar pattern 1000 Hz in Piano mode.

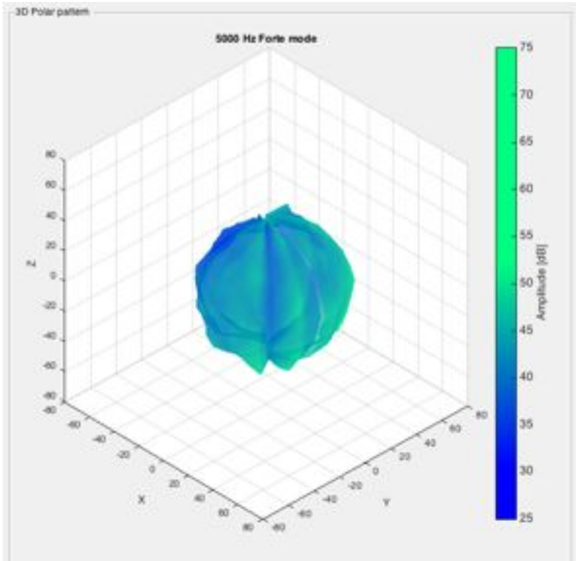

Figure 17. 3D polar pattern 5000 Hz in Forte mode.

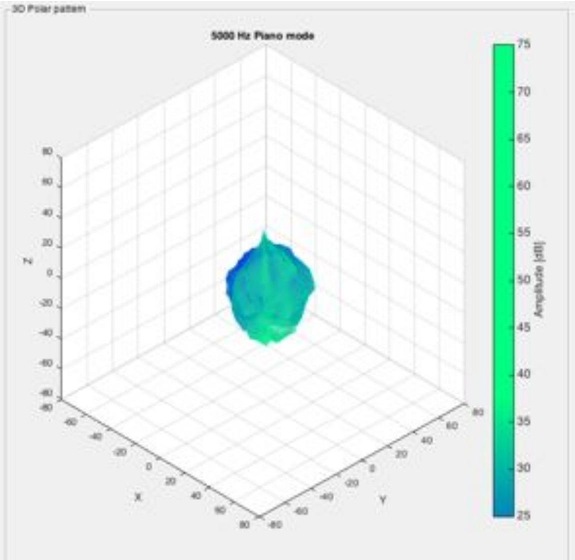

Figure 18. 3D polar pattern 5000 Hz in Piano mode.

All the other 3D polar pattern for both intensities are shown in the Annex.

Analysing the figures, the 400 Hz polar pattern presents more energy than others. Forte mode shows more uniform distribution of energy.

At 1 kHz directivity loses uniformity probably due to the cap resonance that becomes more preponderant over the neck resonance, especially in piano mode where the instrument is presented as more directive in some directions.

Figures 19 to 25 shows the 2D polar pattern for same frequencies and both intensities in planes X=0, Y=0 and Z=0.

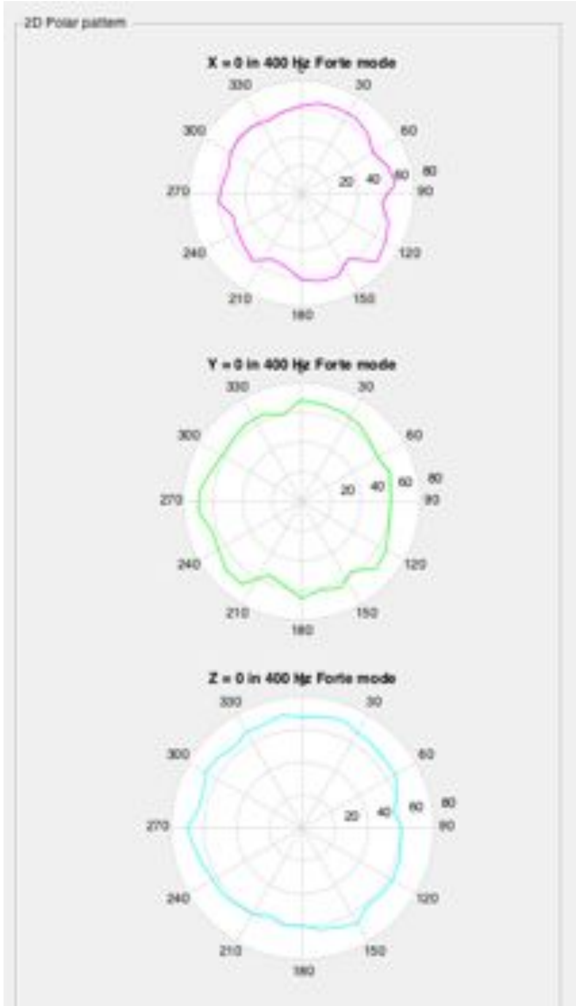

Figure 19. 2D Polar pattern at 400 Hz for forte mode.

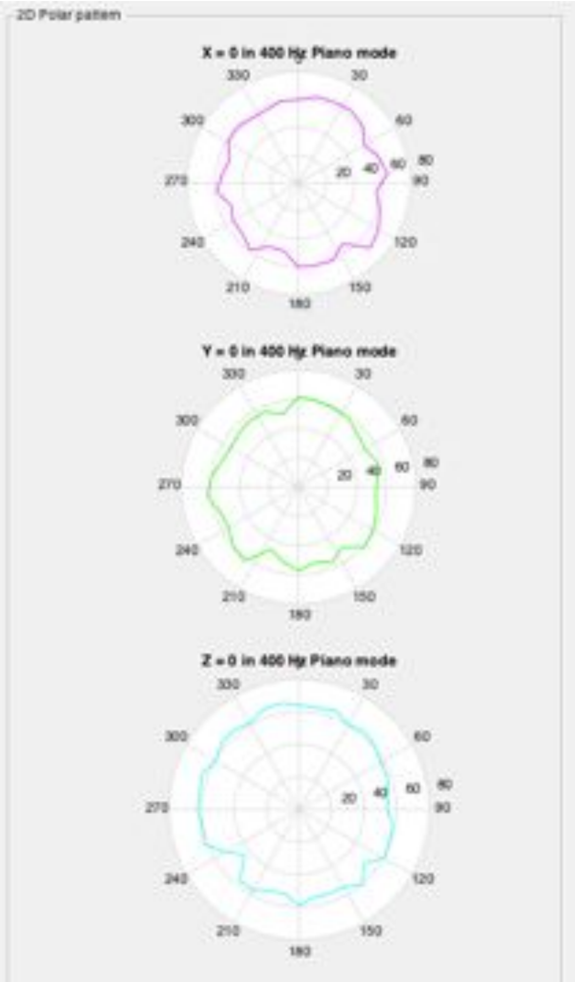

Figure 20. 2D Polar pattern at 400 Hz for piano mode.

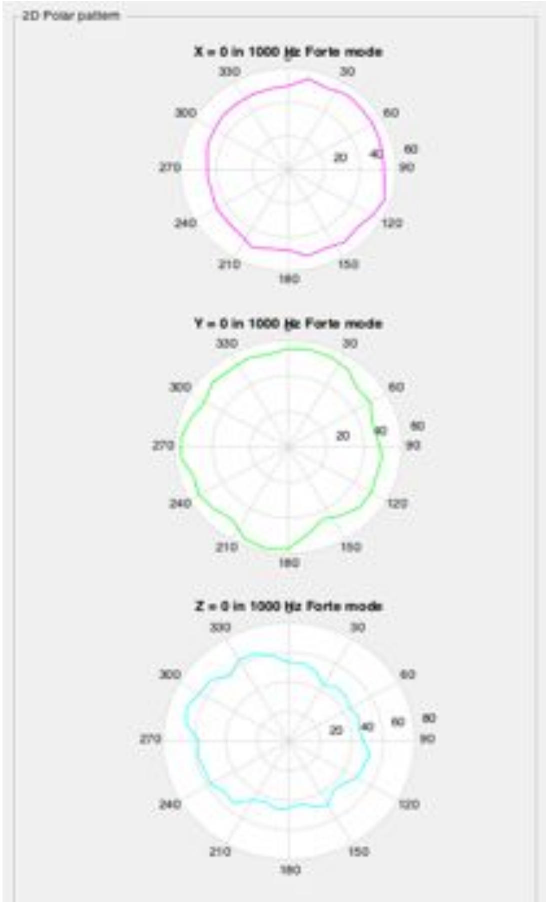

Figure 21. 2D Polar pattern at 1000 Hz for forte mode.

It is clear that at 400 Hz, the instrument does not change the polar pattern form with different intensities.

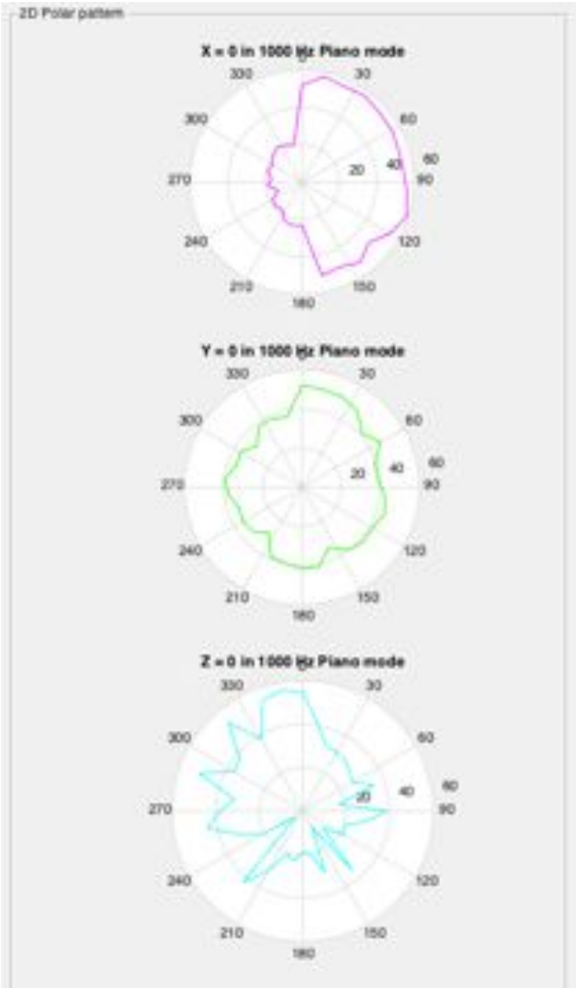

Figure 22. 2D Polar pattern at 1000 Hz for piano mode.

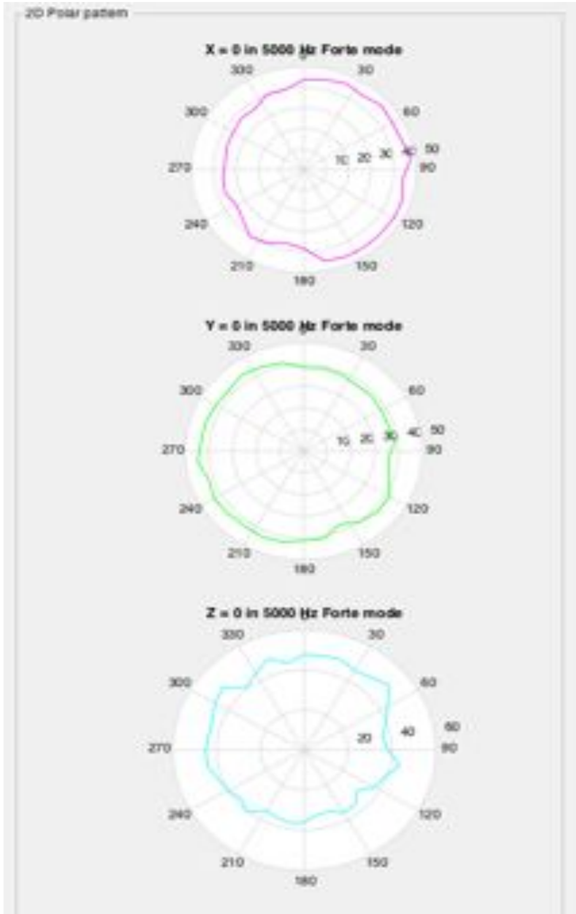

Figure 23. 2D Polar pattern at 5 kHz for forte mode.

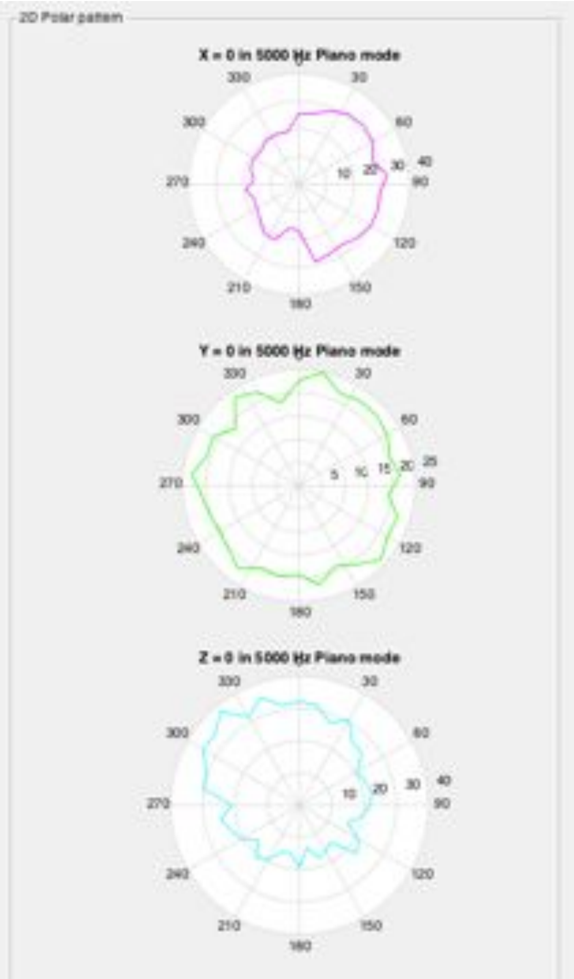

Figure 24. 2D Polar pattern at 5 kHz for piano mode.

For mid and high frequencies, the instrument has a similar behaviour. In axe Z the irradiation is almost the same for both intensities although there is less level between them.

In X=0 it could be seen the difference between the front irradiation at right against back irradiation at left of the figure. There, it is clear that the irradiation between front and back is almost equal for forte mode and there is a big difference in piano mode. That difference is almost 30 dB at 1000 Hz and 10 dB at 5000 Hz.

Finally, in Y=0, the irradiation turns from homogeneous to a form with peaks of mayor intensities in a piano and forte comparison at both frequencies.

At figure 25 and 26 it can be observed the global polar patterns for both modes. It is notorious that directivity focus on 0º (axe Y) for piano mode and it reduces his intensity from 45º to -45º at the back for forte mode. That level difference may be refer to reflections on the floor that do not had enough absorbent material. There are two possible consequences on this problem when we analyse results, both due to comb filters. If the sum is constructive at the frequency of analysis the polar pattern diagram shows more intensity that it should and if the sum is destructive the problem will be the attenuation.

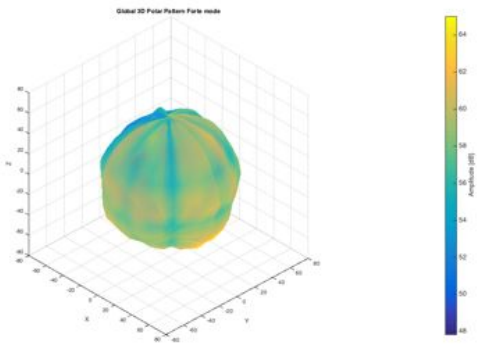

Figure 25. Global 3D Polar pattern Forte mode.

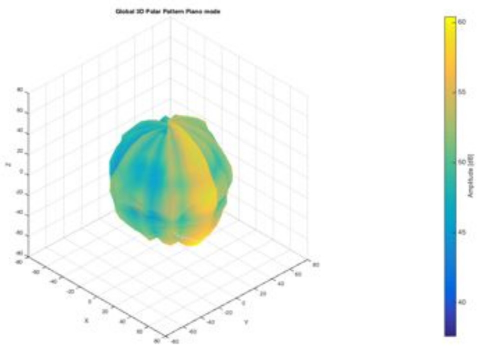

Figure 26. Global 3D Polar Pattern Piano mode.

From figure 27 to 32 the piano and forte mode may be seen for each plane (XY, ZY and XZ) as sonograms.

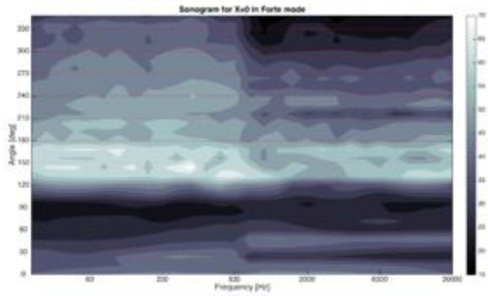

Figure 27. Sonogram for x=0 in Forte mode.[4]

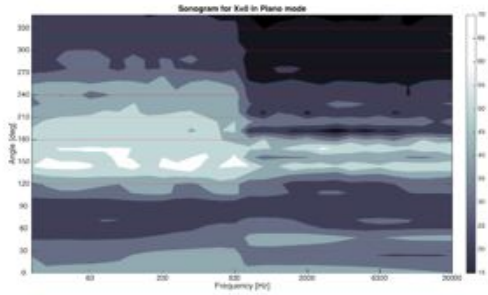

Figure 28. Sonogram for x=0 in Piano mode.

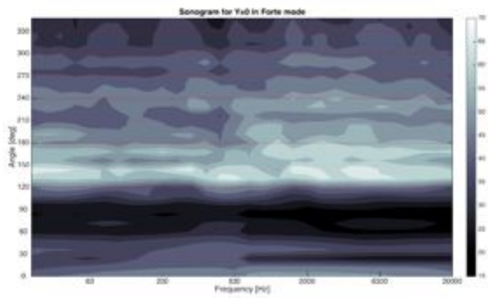

Figure 29. Sonogram for y=0 in Forte mode.

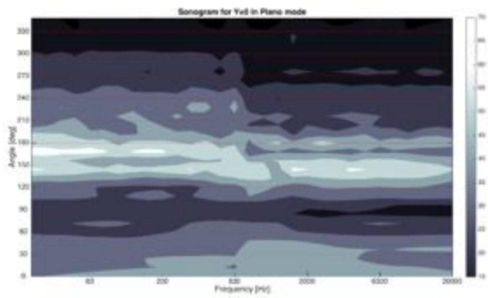

Figure 30. Sonogram for y=0 in Piano mode.

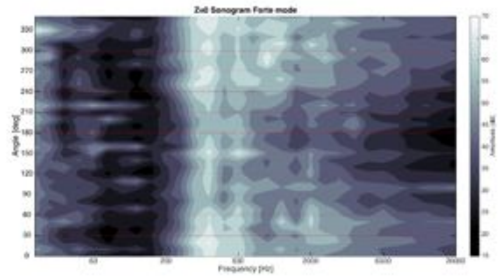

Figure 31. Sonogram for z=0 in Forte mode.

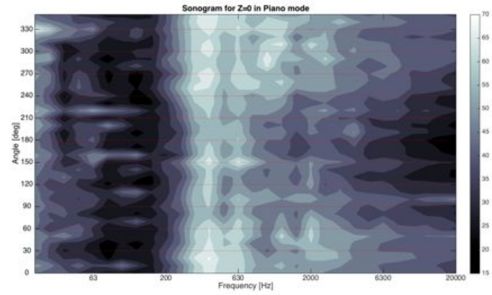

Figure 32. Sonogram for z=0 in Piano mode.

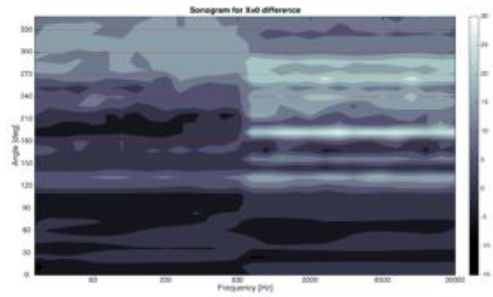

Figure 33. Sonogram difference for x=0.

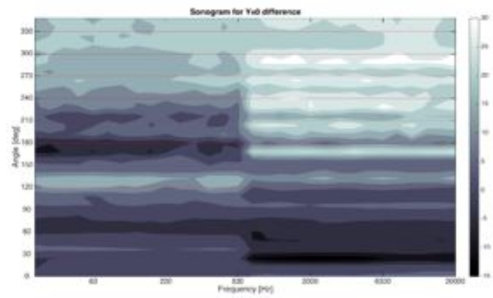

Figure 34. Sonogram difference for y =0.

[4] In order to have a better appreciation the figure is present in annex C

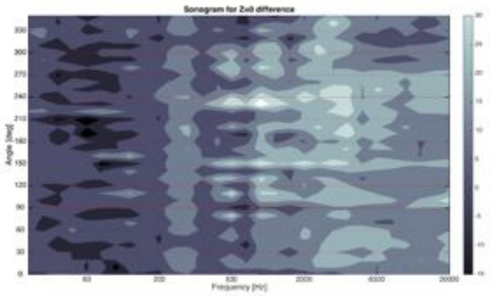

Figure 35. Sonogram difference for z=0.

In order to have a better appreciation all the sonogram figures are present in annex C.

6. CONCLUSIONS

Results show that, for this kind of instrument, polar pattern is having not a lineal behaviour. Is not possible to assume that directivity is independent from frequency, played tone and dynamics. Results shows that the polar pattern of cavaquinho changes with the change of intensity and played tone. Under this knowledge is essential to work in order to obtain better polar patterns of different instrument based on dynamic change, this will become a fundamental tool for acoustic designs and music recordings.

The polar pattern is not a static specification and it cannot be simply widespread to other instrument of the same family. String instruments usually have a mouth (sometimes more) and it has been verified that as a Helmhotlz resonator the mouth support an important part for low frequencies. At this point it behaves more as omnidirectional.

The implementation for processing results has been really useful and it becomes a powerful tool. It can be improved to be faster so that the postprocessing becomes easier.

For further works it is necessary to implement a more precise system for the microphones arrangement. Besides the results where admissible, a system that allows the measure to be repeatable is necessary.

The information generated is considered a really good material considering that does not exist an investigation of acoustical behaviour of this instrument before.

7. DISCUSSION

It is clear that the analysis shows difference for both intensities but these different intensities also has another difference that is based in the technique by playing the instrument. This was not considered at the first time under Lokki's affirmations of spherical propagation. Results may have errors based on the pick and finger play which are another variable that was not constant under the measure. It may be possible that the change of polar pattern come either from the change of intensity or the change of technique to excite the rope.

Even if this decision was correctly made the precision of a musician is not truly constant to excite the rope. It is necessary to apply a mechanic system with a control that allow every measurement repetition exactly the same. This may be an electrodynamic exciter as used by Meyer (c.b.) but this system will avoid the influence of the performer which is inherent to the instrument. It will be necessary for further works to improve the anechoic conditions of the camera to avoid unexpected reflections that upset the results, specially from the wood floor and the reflective furniture used to achieve the highest microphone positions.

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[3] Meyer, Jurgen. *"Directivity of the Bowed Stringed Instruments and Its Effect on Orchestral Sound in Concert Halls",* Physikalisch-Technisch Beundesanstalt, Braunschweig, West Germany. 1971.

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[5] Felipe Otondo and Jens Holger Rindel,, *"Directivity of musical instruments in a real performance situation"* Ørsted-DTU, Acoustic Technology, Technical University of Denmark, Denmark. 2001.

[6] Beranek, Leo. *"Acoustic"* Second edition. Acoustic Laboratory, Massachusetts. 1961.

[7] Heinrich Kuttruff "Room Acoustics" Fourth Edition. Institut für Technische Akustik, Technische Hochschule Aachen, Aachen, Germany 1973.

[8] UNE EN ISO 3382 Acoustics Measurements of room acoustic parameters. 2009.

ANNEX A - 2D and 3D polar patterns

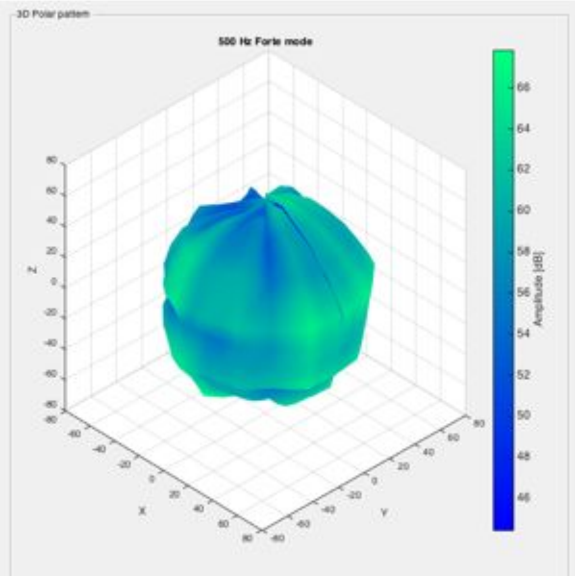

Figure 36. 3D polar pattern 500 Hz in Forte mode.

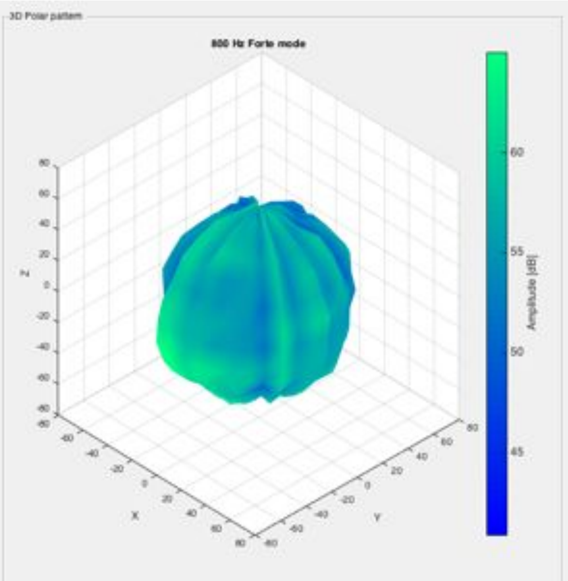

Figure 38. 3D polar pattern 800 Hz in Forte mode.

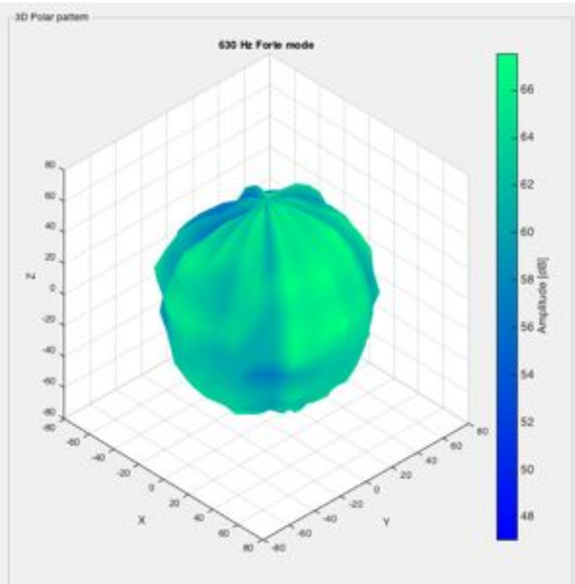

Figure 37. 3D polar pattern 630 Hz in Forte mode.

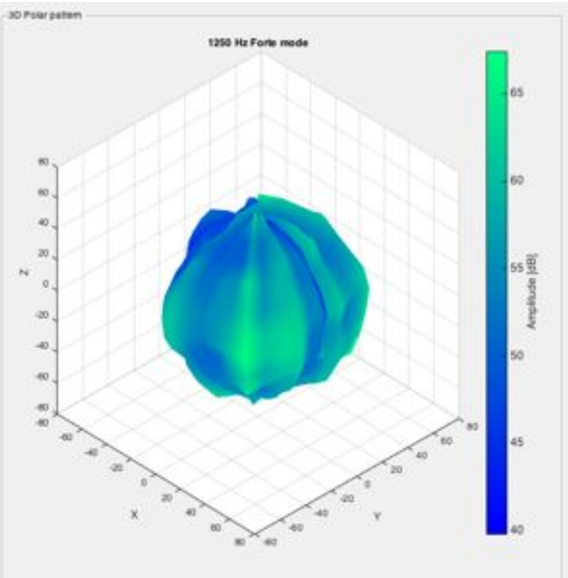

Figure 39. 3D polar pattern 1250 Hz in Forte mode.

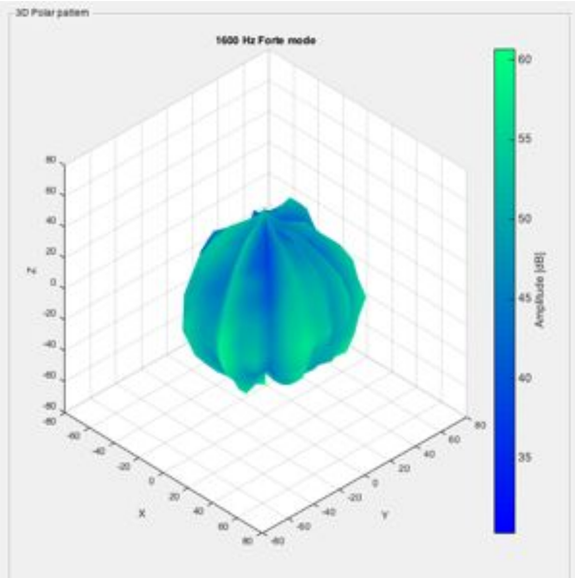

Figure 40. 3D polar pattern 1600 Hz in Forte mode.

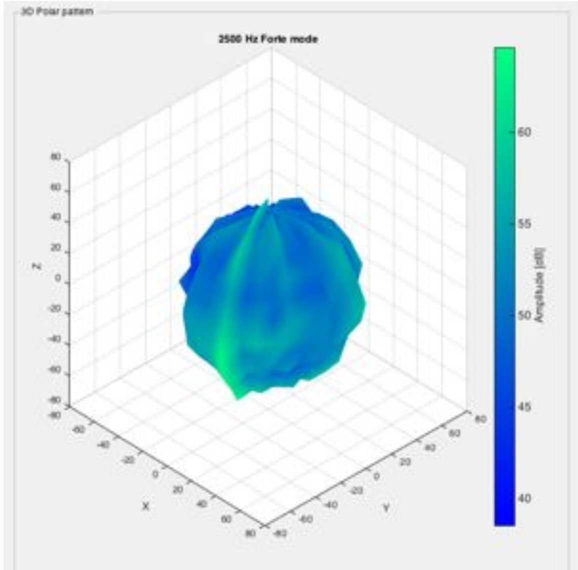

Figure 42. 3D polar pattern 2500 Hz in Forte mode.

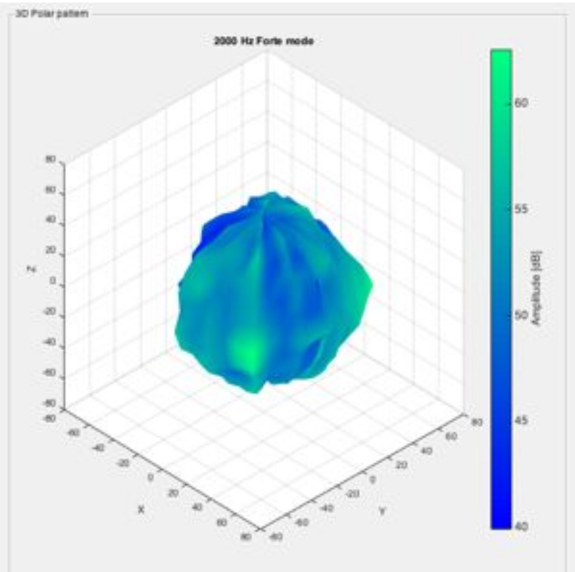

Figure 41. 3D polar pattern 2000 Hz in Forte mode.

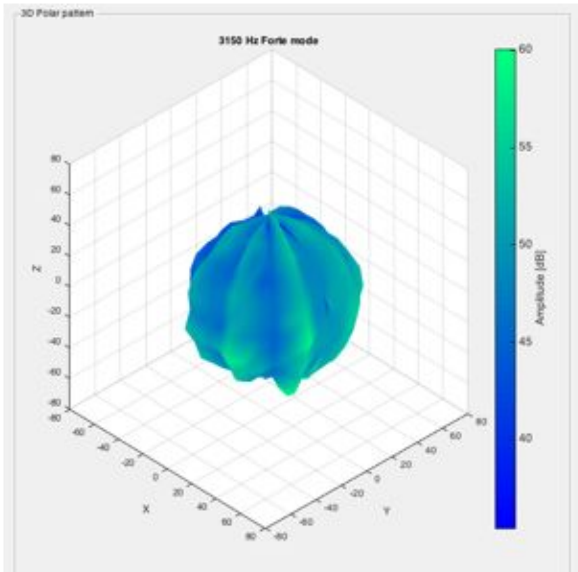

Figure 43. 3D polar pattern 3150 Hz in Forte mode.

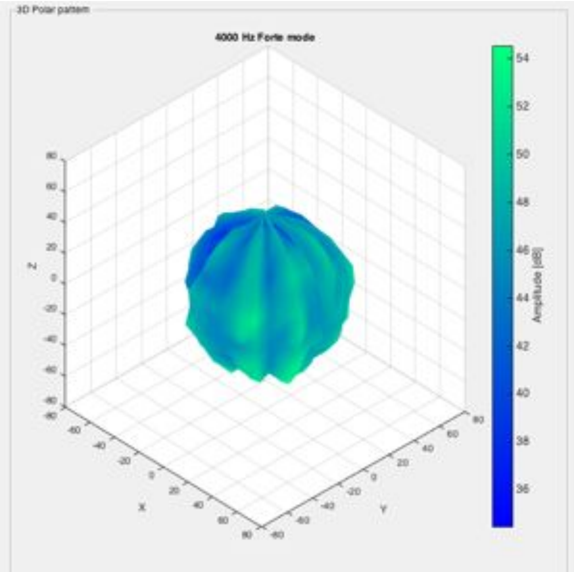

Figure 44. 3D polar pattern 4000 Hz in Forte mode.

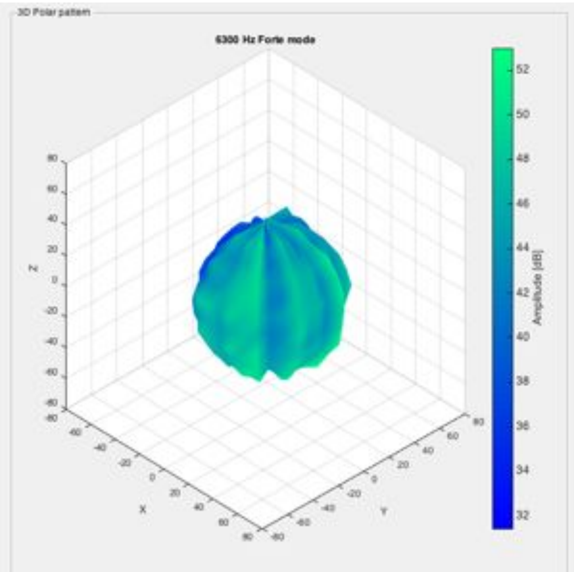

Figure 45. 3D polar pattern 6300 Hz in Forte mode.

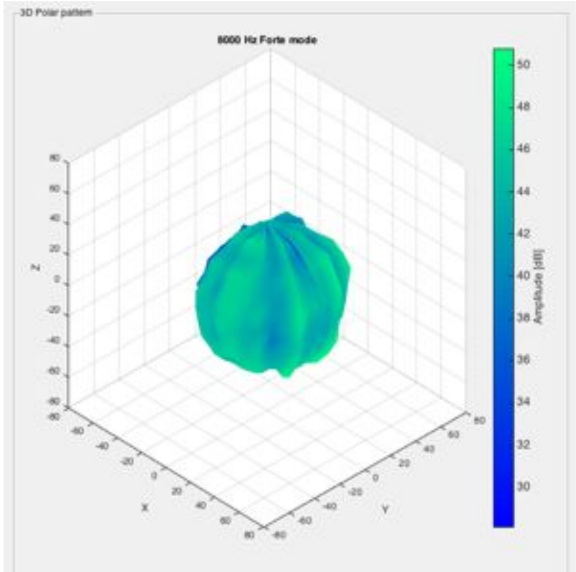

Figure 46. 3D polar pattern 8000 Hz in Forte mode.

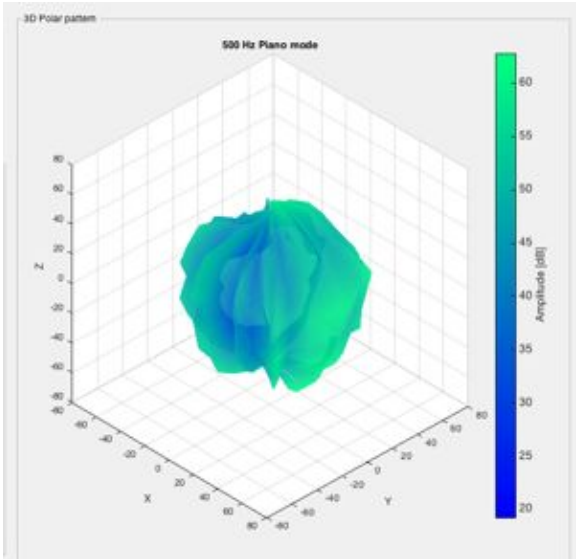

Figure 47. 3D polar pattern 500 Hz in Piano mode.

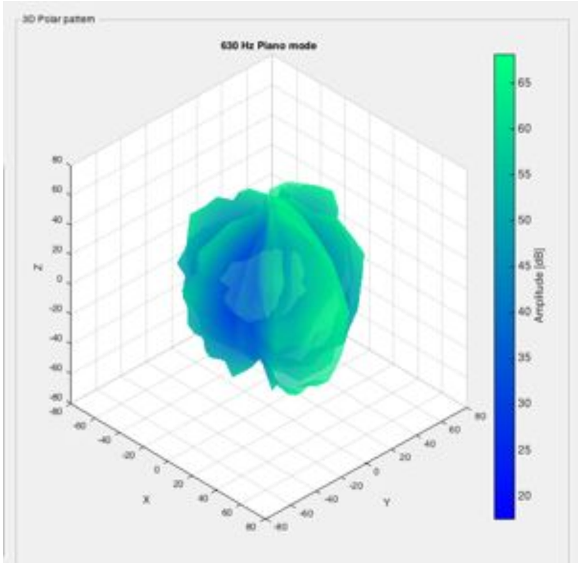

Figure 48. 3D polar pattern 630 Hz in Piano mode.

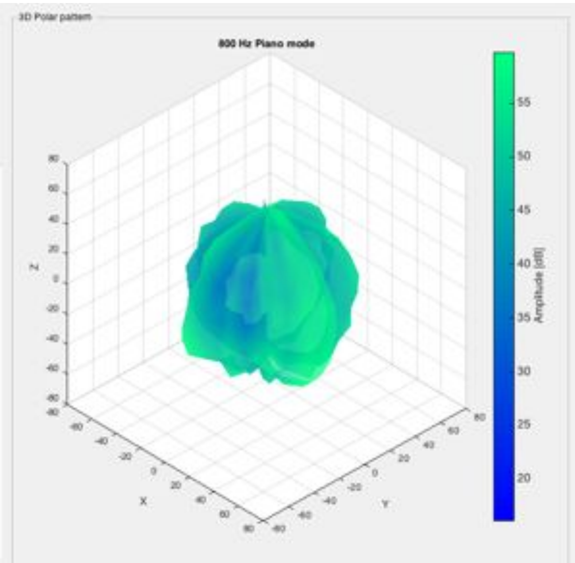

Figure 49. 3D polar pattern 800 Hz in Piano mode.

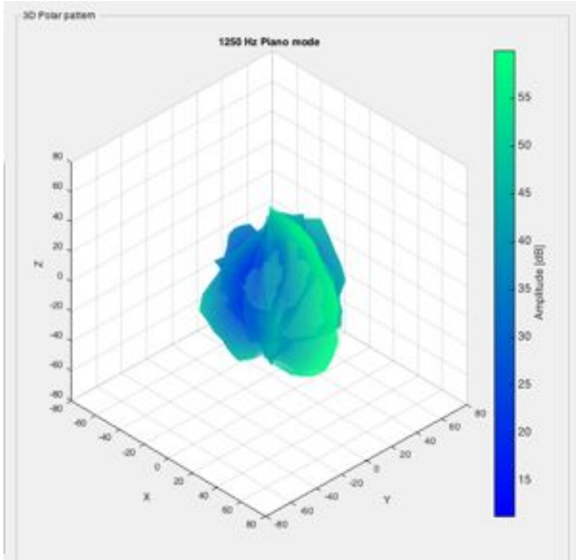

Figure 50. 3D polar pattern 1250 Hz in Piano mode.

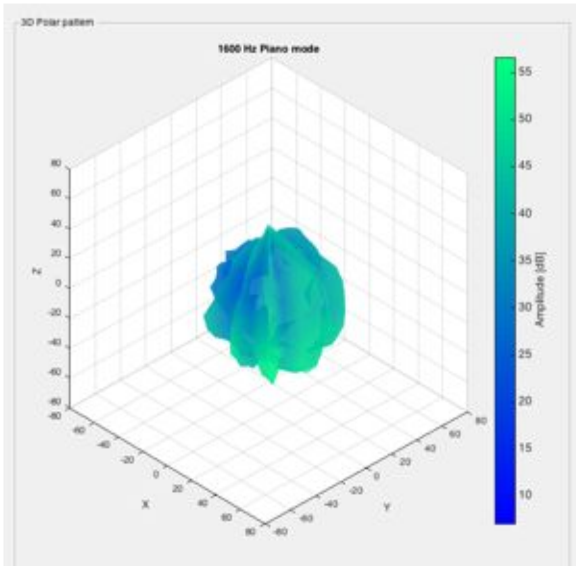

Figure 51. 3D polar pattern 1600 Hz in Piano mode.

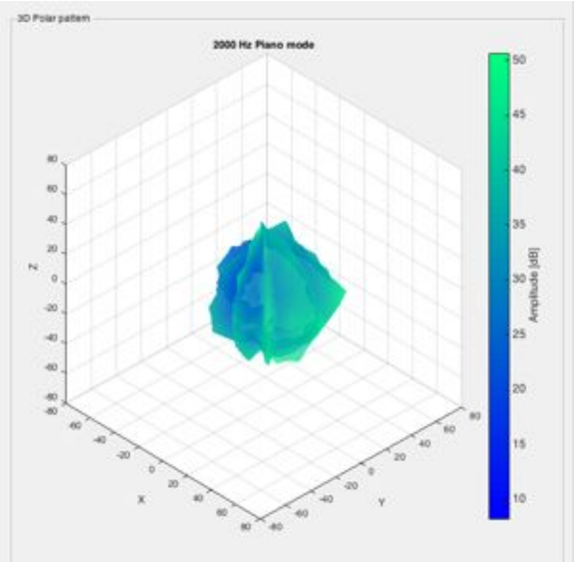

Figure 52. 3D polar pattern 2000 Hz in Piano mode.

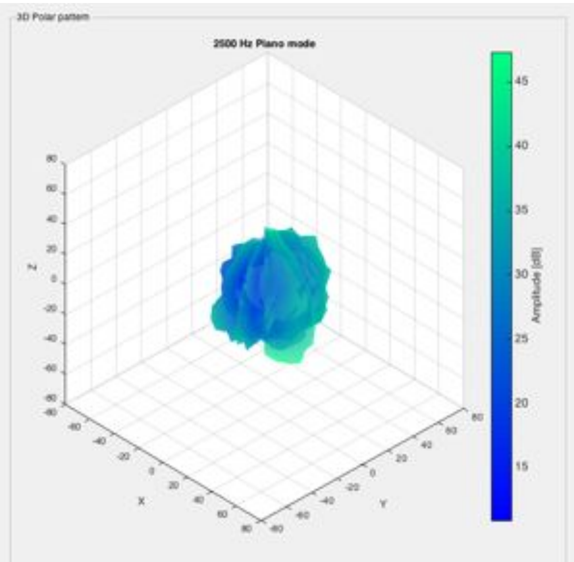

Figure 53. 3D polar pattern 2500 Hz in Piano mode.

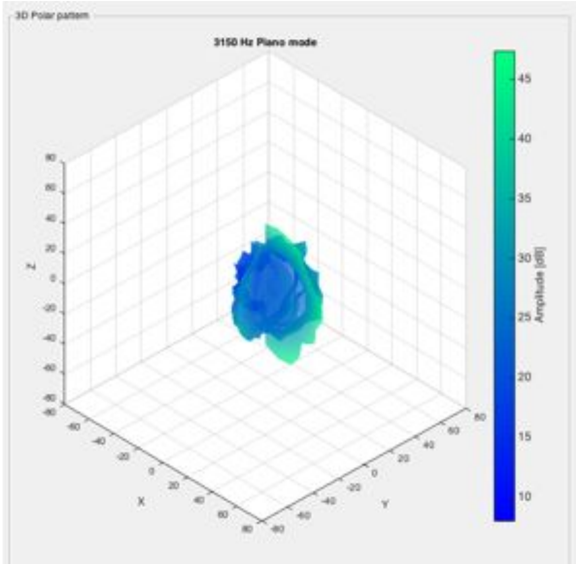

Figure 54. 3D polar pattern 3150 Hz in Piano mode.

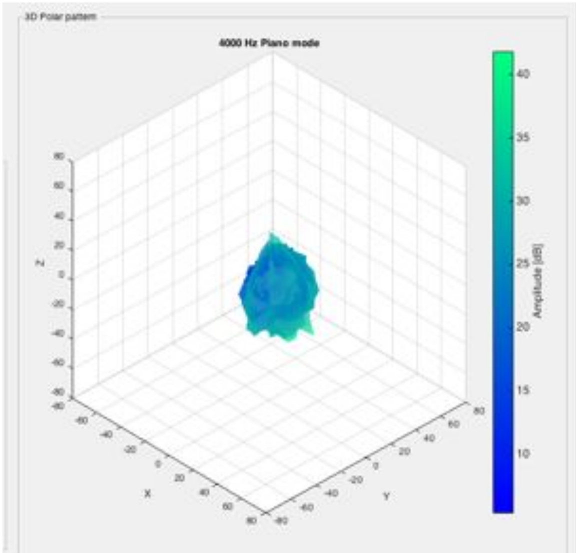

Figure 55. 3D polar pattern 4000 Hz in Piano mode.

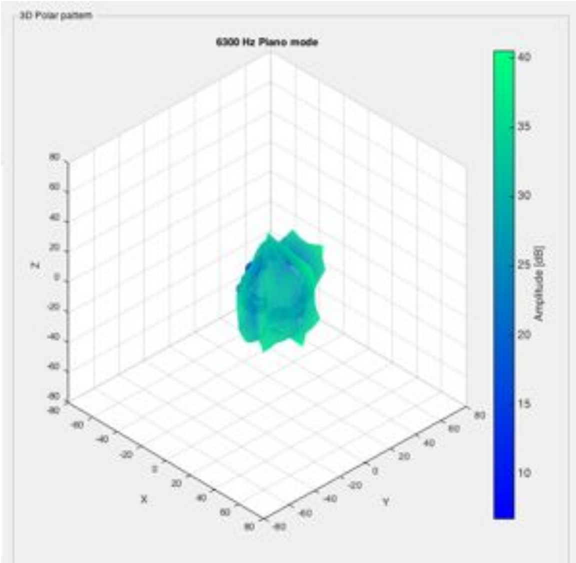

Figure 56. 3D polar pattern 6300 Hz in Piano mode.

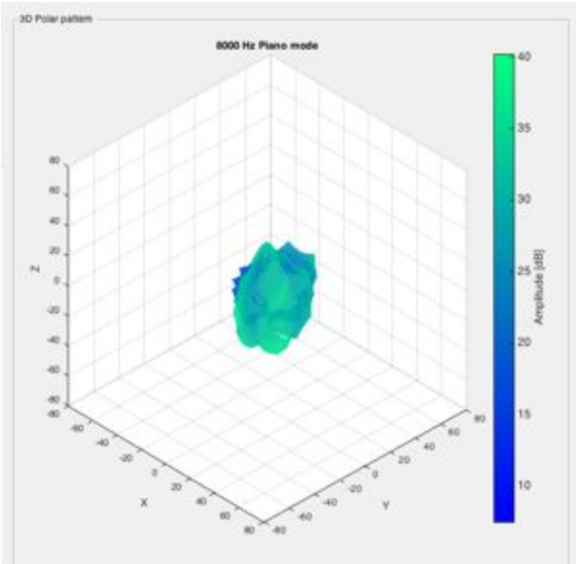

Figure 57. 3D polar pattern 8000 Hz in Piano mode.

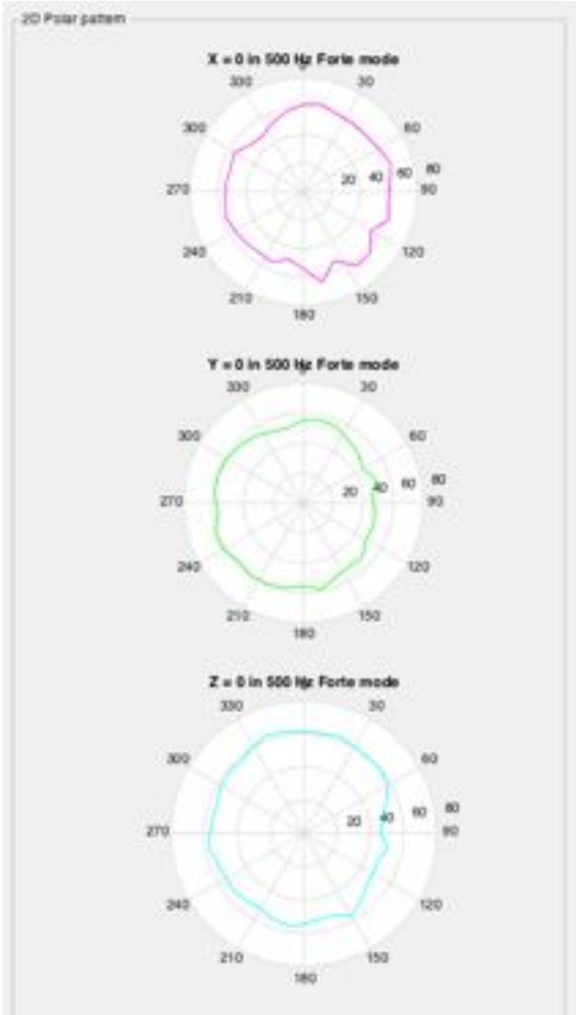

Figure 58. 2D polar pattern 500 Hz in Forte mode.

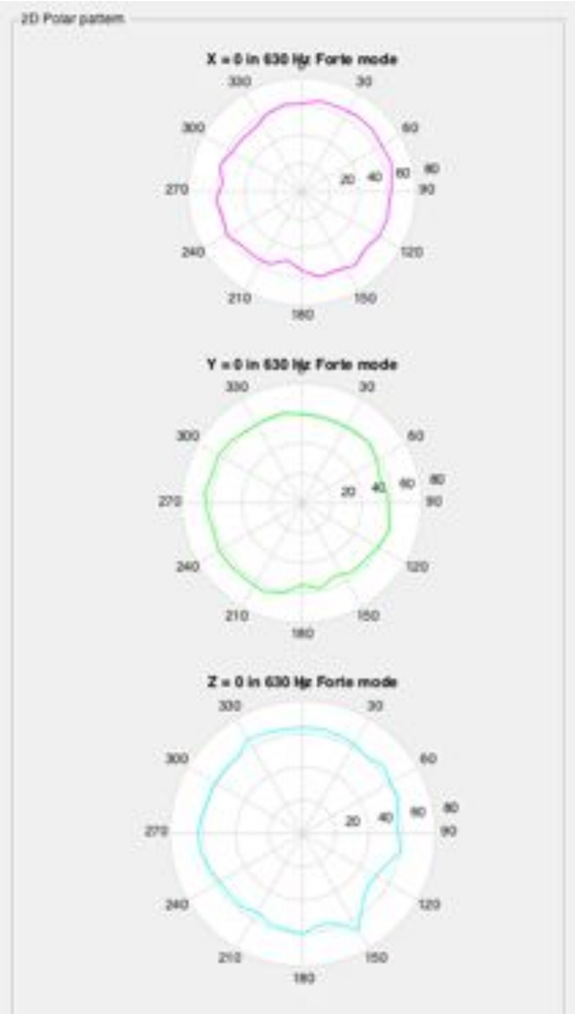

Figure 59. 2D polar pattern 630 Hz in Forte mode.

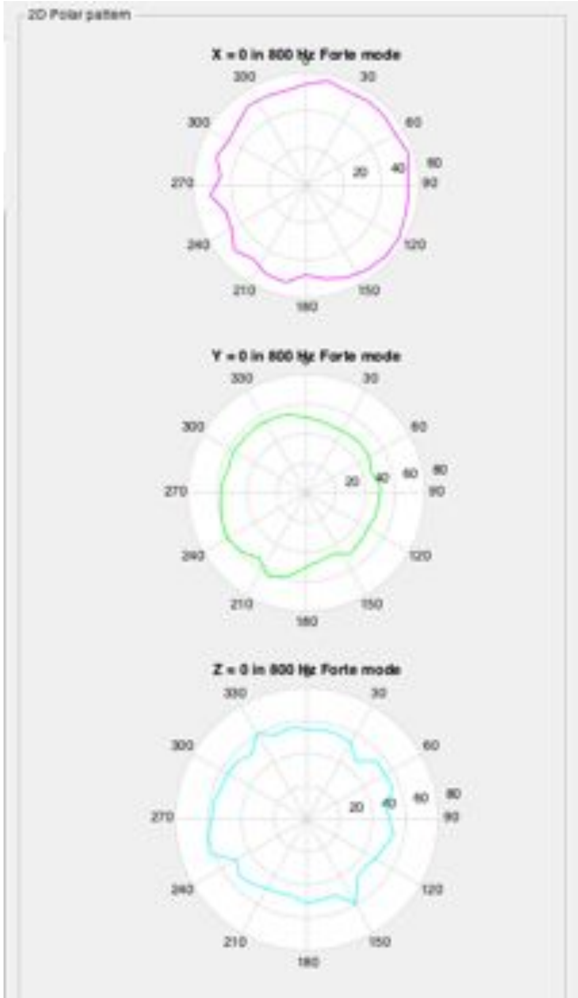

Figure 60. 2D polar pattern 800 Hz in Forte mode.

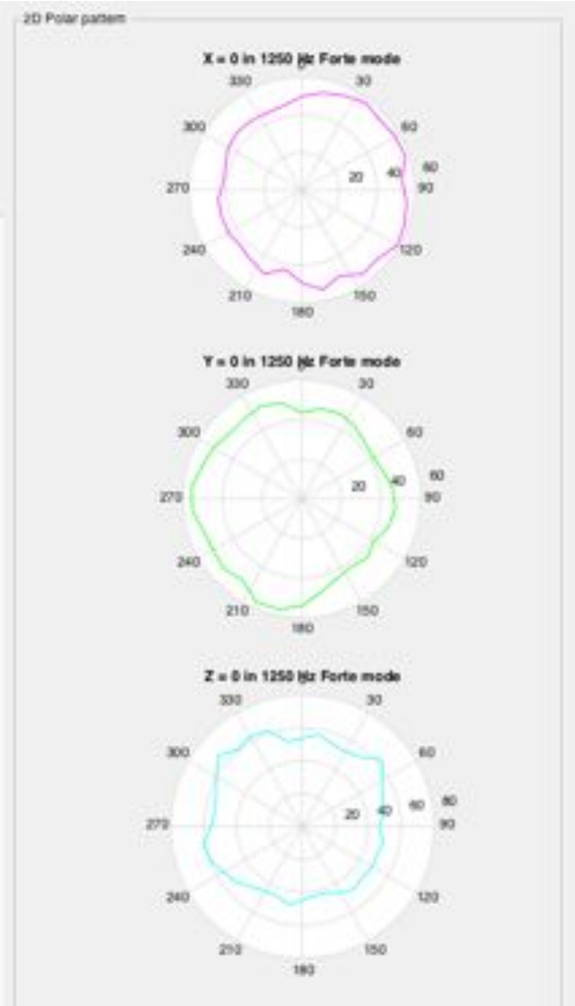

Figure 61. 2D polar pattern 1250 Hz in Forte mode.

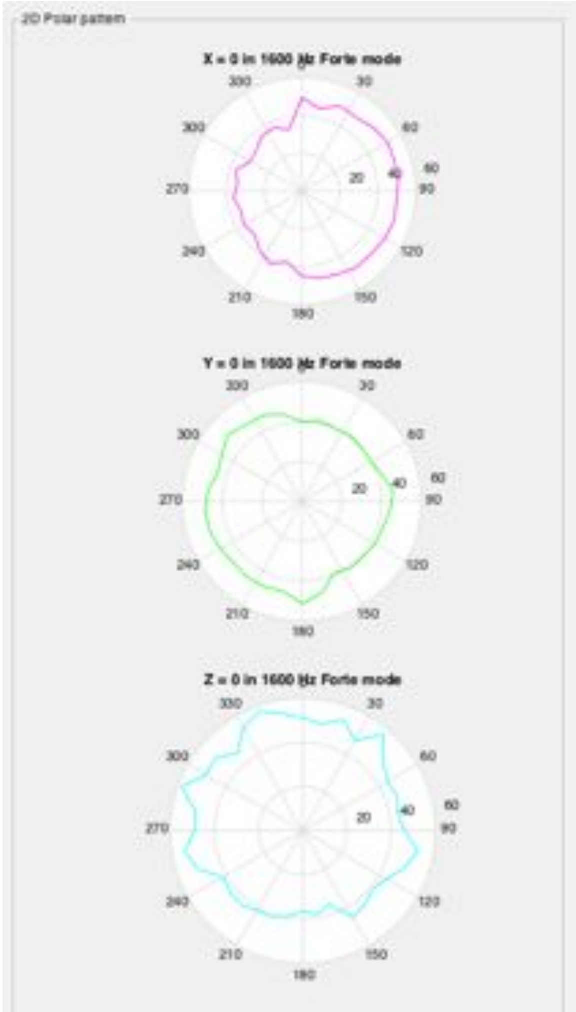

Figure 62. 2D polar pattern 1600 Hz in Forte mode.

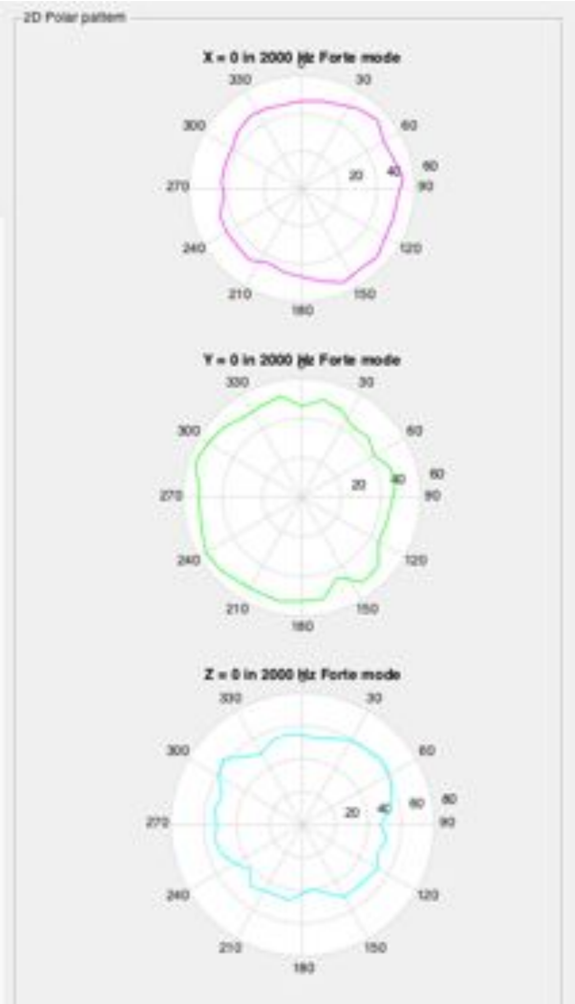

Figure 63. 2D polar pattern 2000 Hz in Forte mode.

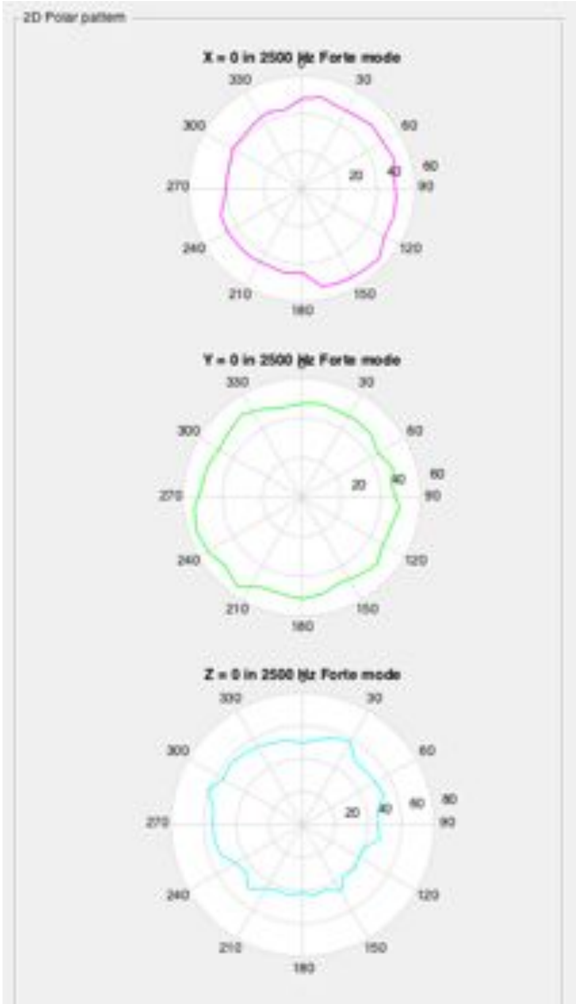

Figure 64. 2D polar pattern 2500 Hz in Forte mode.

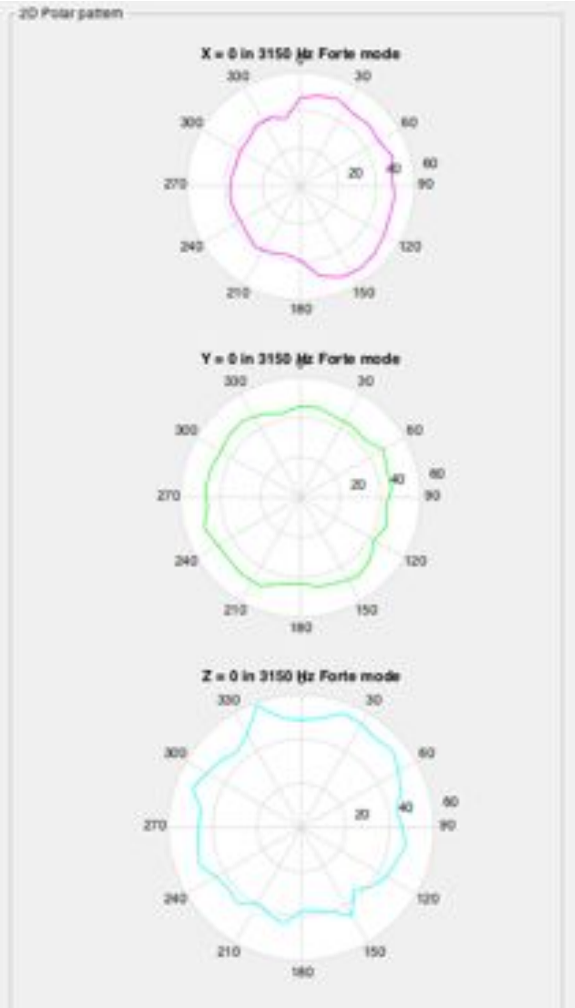

Figure 65. 2D polar pattern 3150 Hz in Forte mode.

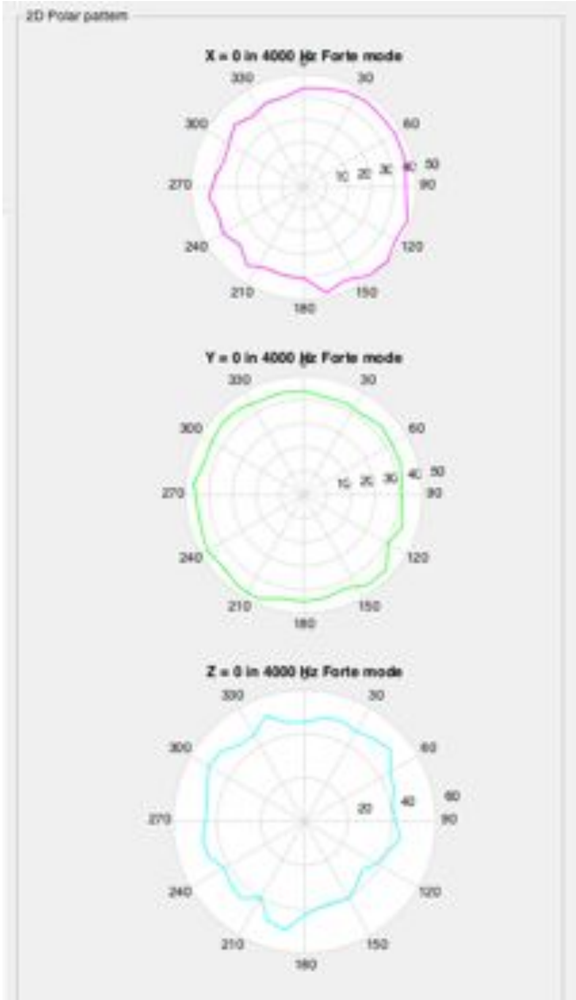

Figure 66. 2D polar pattern 4000 Hz in Forte mode.

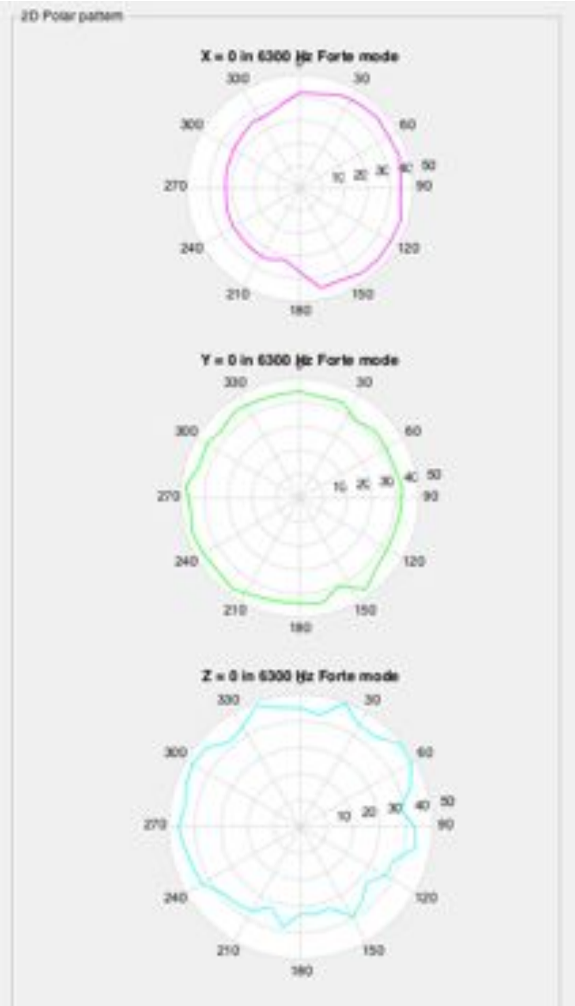

Figure 67. 2D polar pattern 6300 Hz in Forte mode.

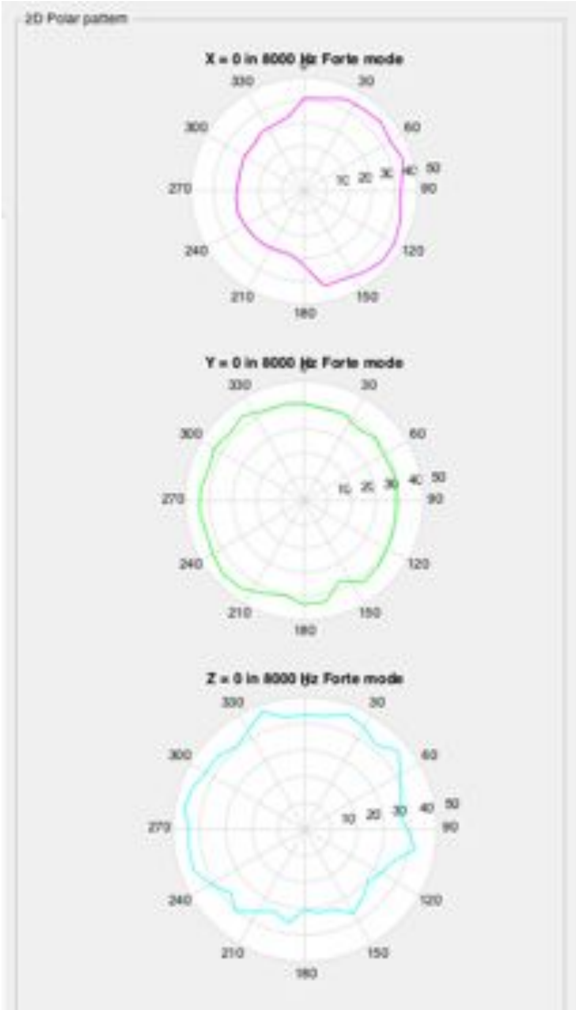

Figure 68. 2D polar pattern 8000 Hz in Forte mode.

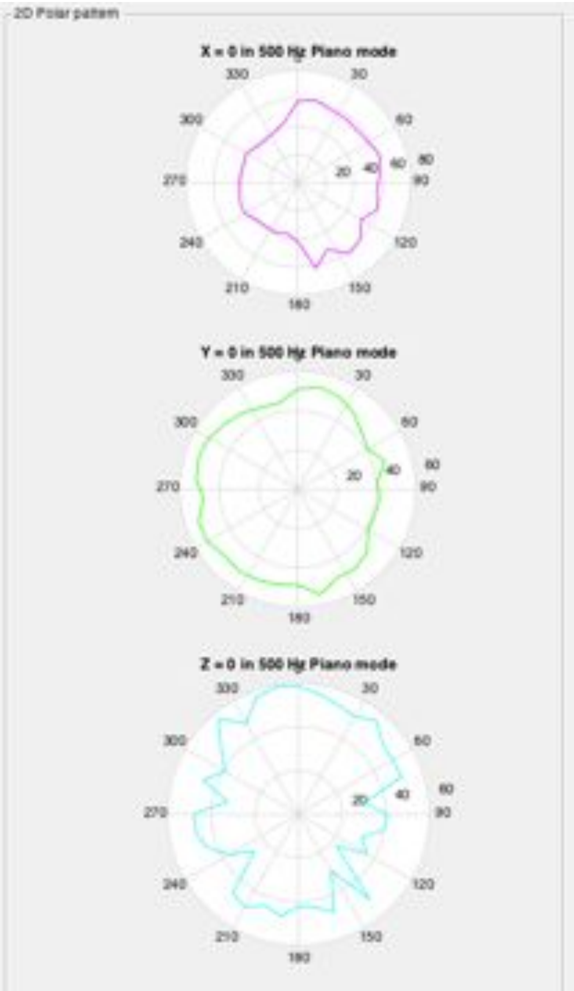

Figure 69. 2D polar pattern 500 Hz in Piano mode.

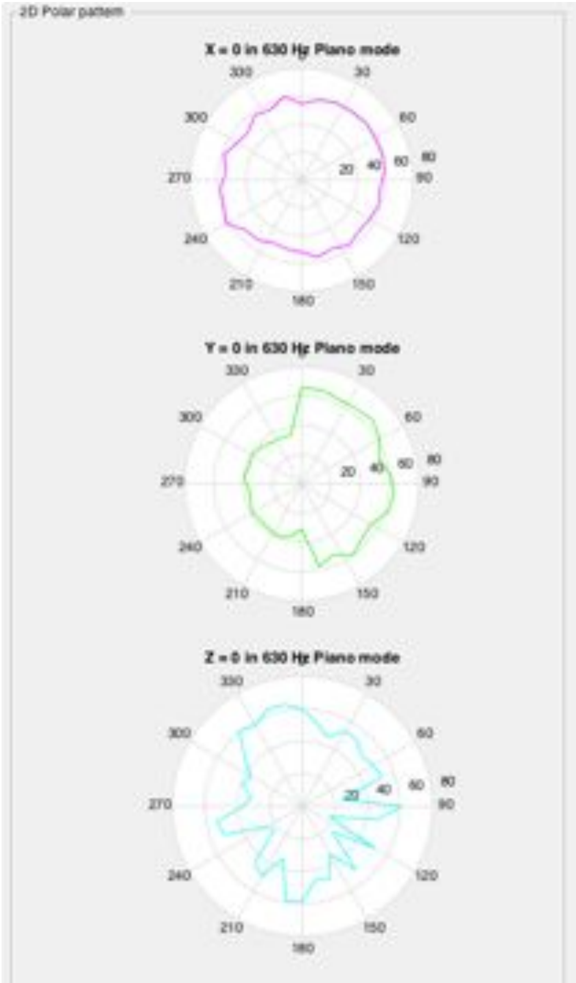

Figure 70. 2D polar pattern 630 Hz in Piano mode.

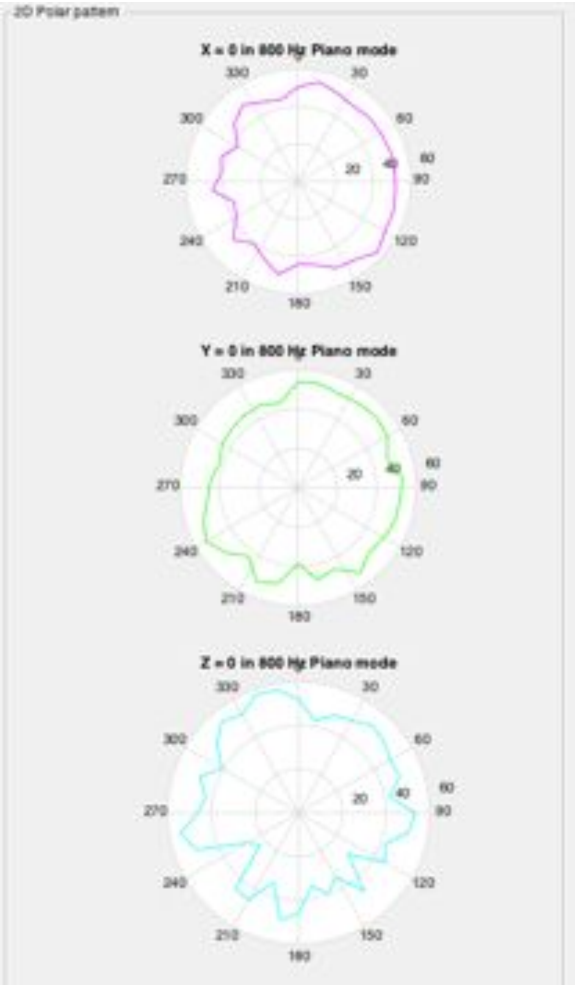

Figure 71. 2D polar pattern 800 Hz in Piano mode.

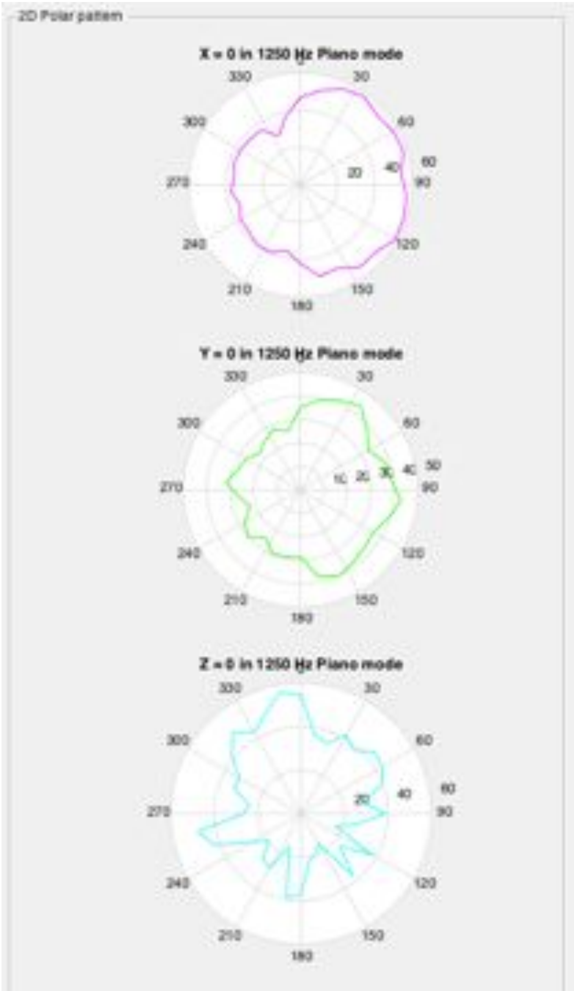

Figure 72. 2D polar pattern 1250 Hz in Piano mode.

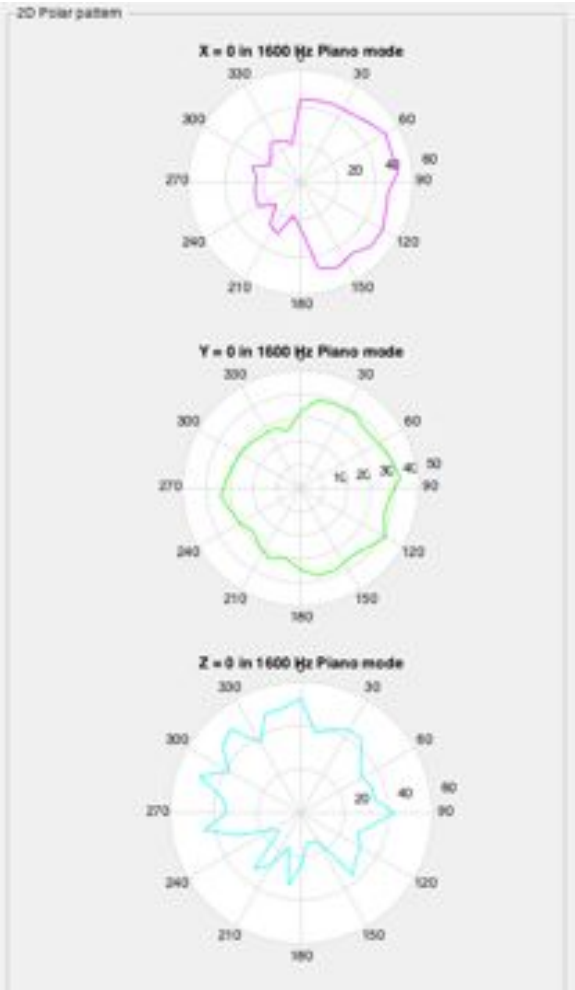

Figure 73. 2D polar pattern 1600 Hz in Piano mode.

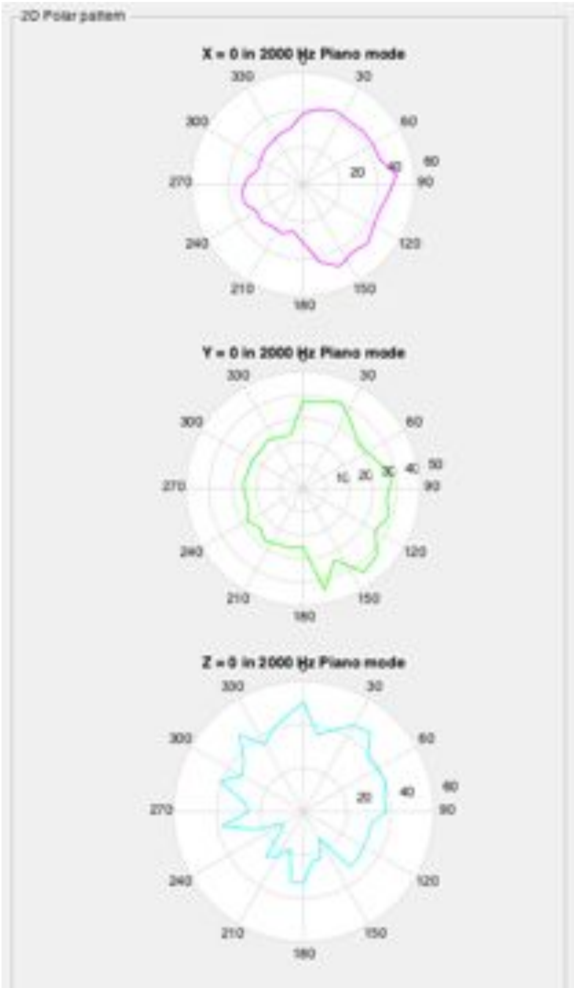

Figure 74. 2D polar pattern 2000 Hz in Piano mode.

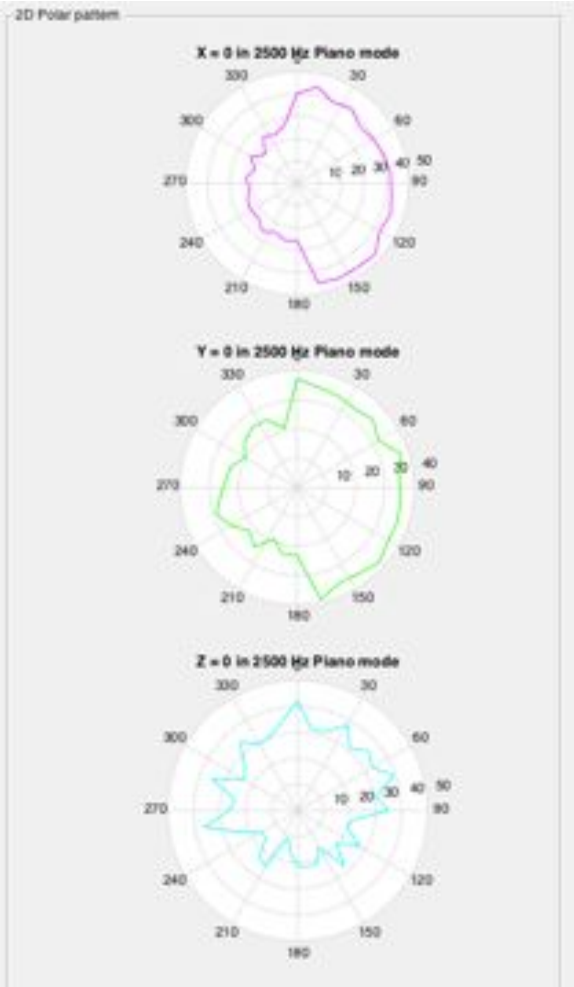

Figure 75. 2D polar pattern 2500 Hz in Piano mode.

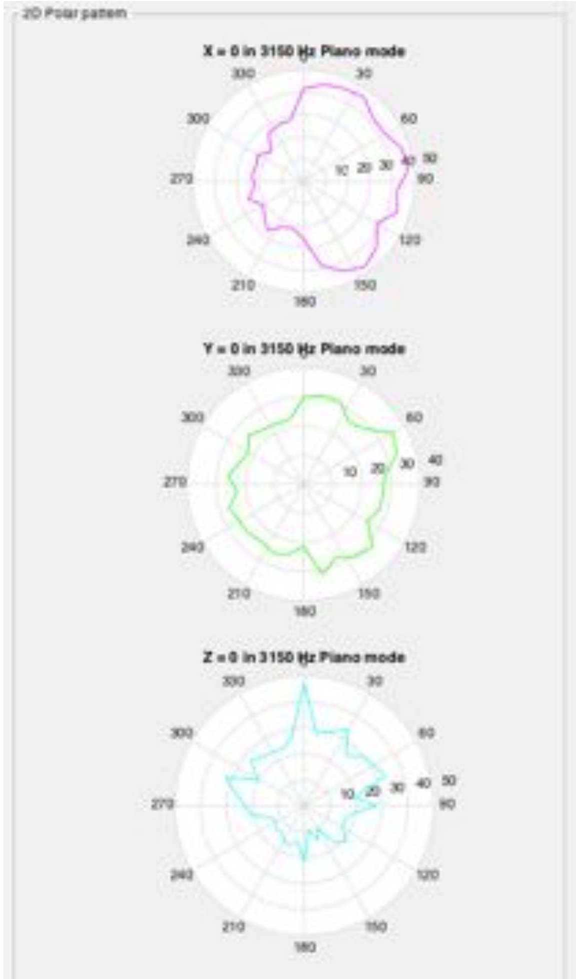

Figure 76. 2D polar pattern 3150 Hz in Piano mode.

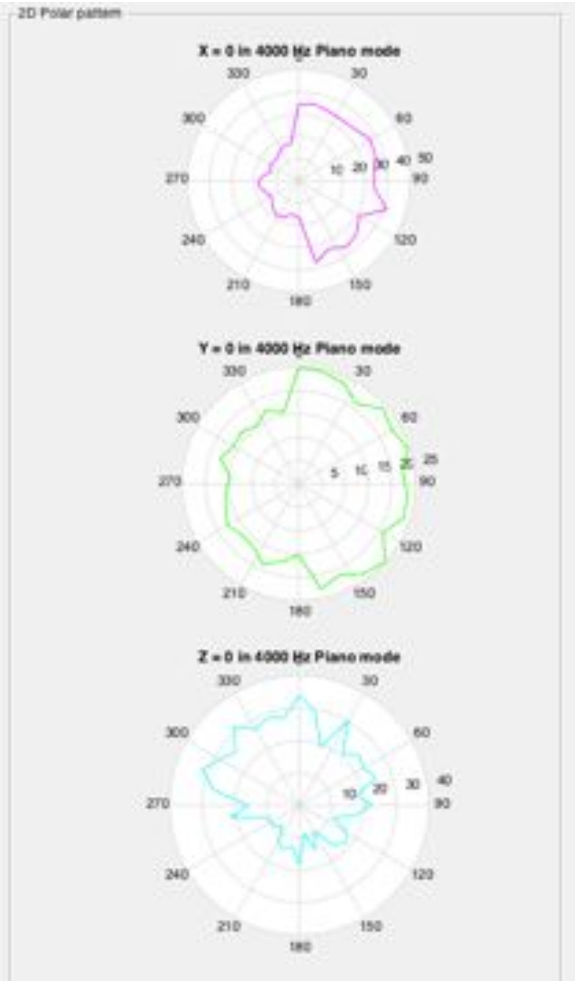

Figure 77. 2D polar pattern 4000 Hz in Piano mode.

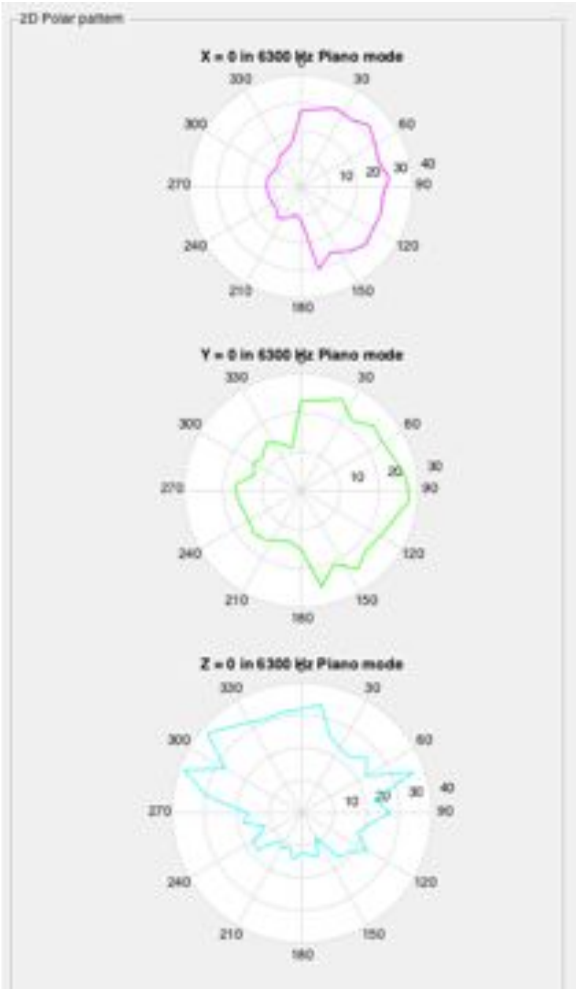

Figure 78. 2D polar pattern 6300 Hz in Piano mode.

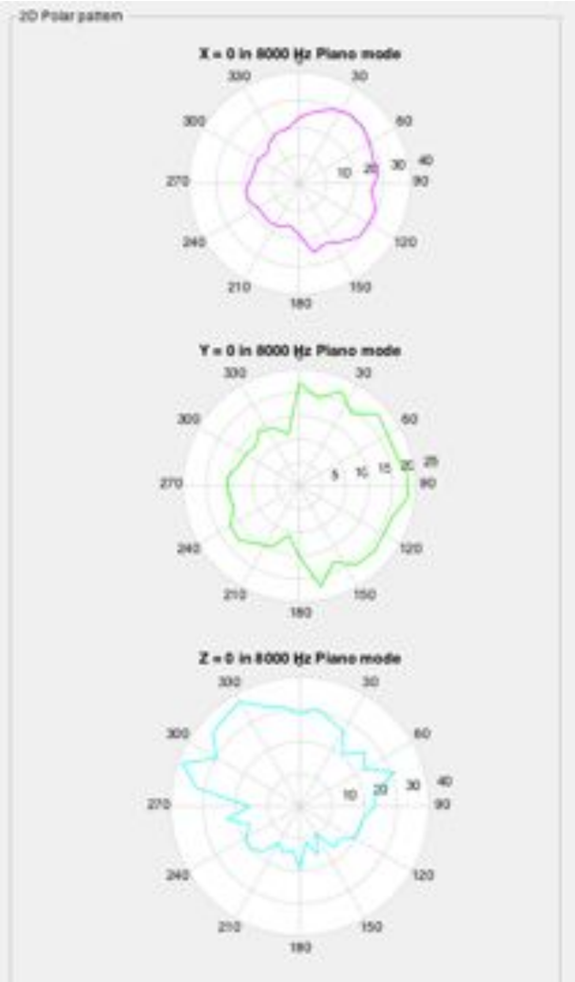

Figure 79. 2D polar pattern 8000 Hz in Piano mode.

Annex B - Calculations

Critical distance:

$$Cd = 0{,}06 \; x \; \sqrt{\frac{V}{RT}}$$

where

$$V = 10 \; x \; 5{,}7 \; x \; 8{,}2 \; = 467{,}40 \; m^3$$

RT= 0,64 s

taking the worst case, with lower frequency 250 Hz.

So,

Cd=1,62 m

k.r term:

$$k = \frac{2\pi f}{c}$$

Where

f = 250 Hz
c = 343 $\frac{m}{s}$
r = 1,4 m

So,
k.r = 6,4

Annex C – Extended figures

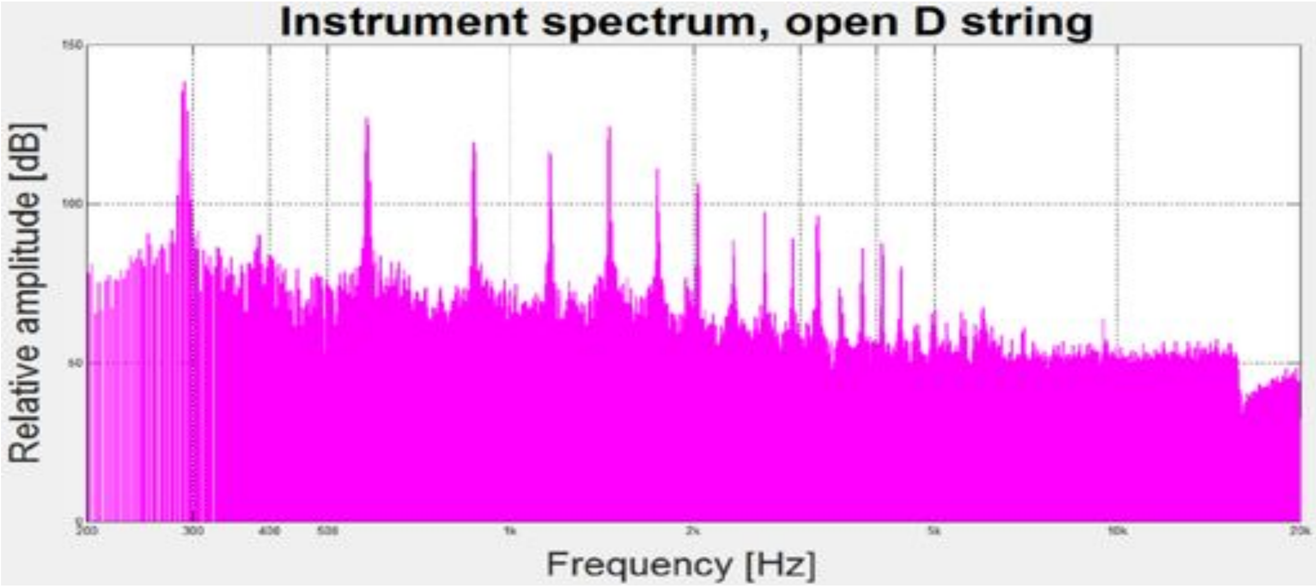

Figure 3. Preliminary analysis of spectrum

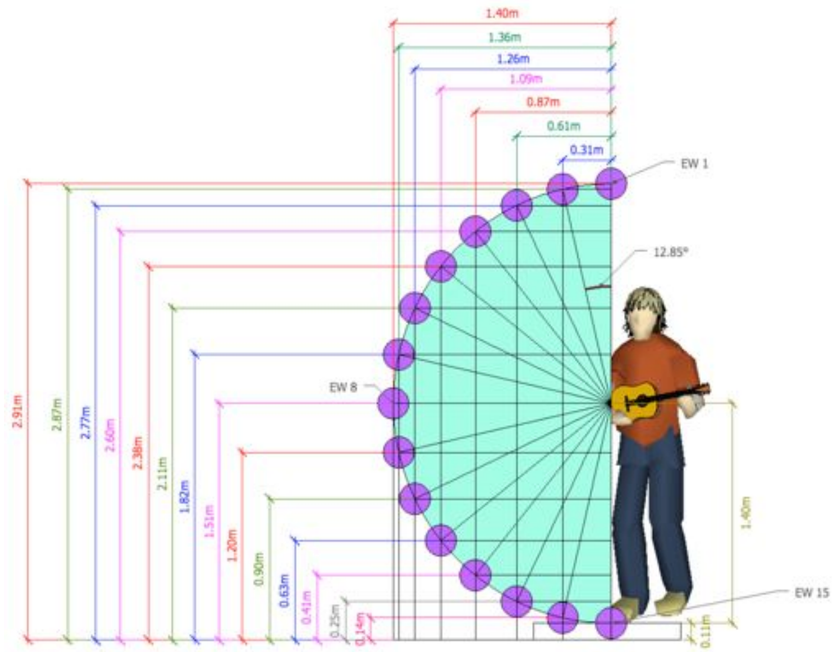

Figure 9. Disposition of the microphones arrangement

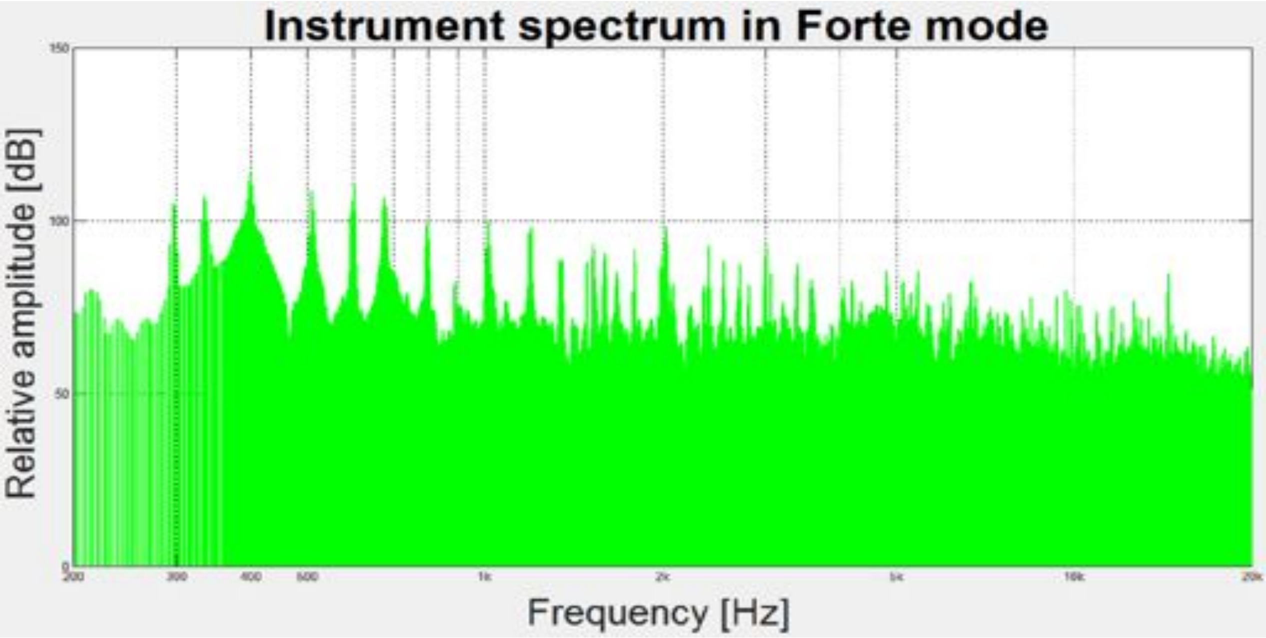

Figure 12. Continuum spectrum of analysed signal in Forte mode measure in 0 degrees with EW 8.

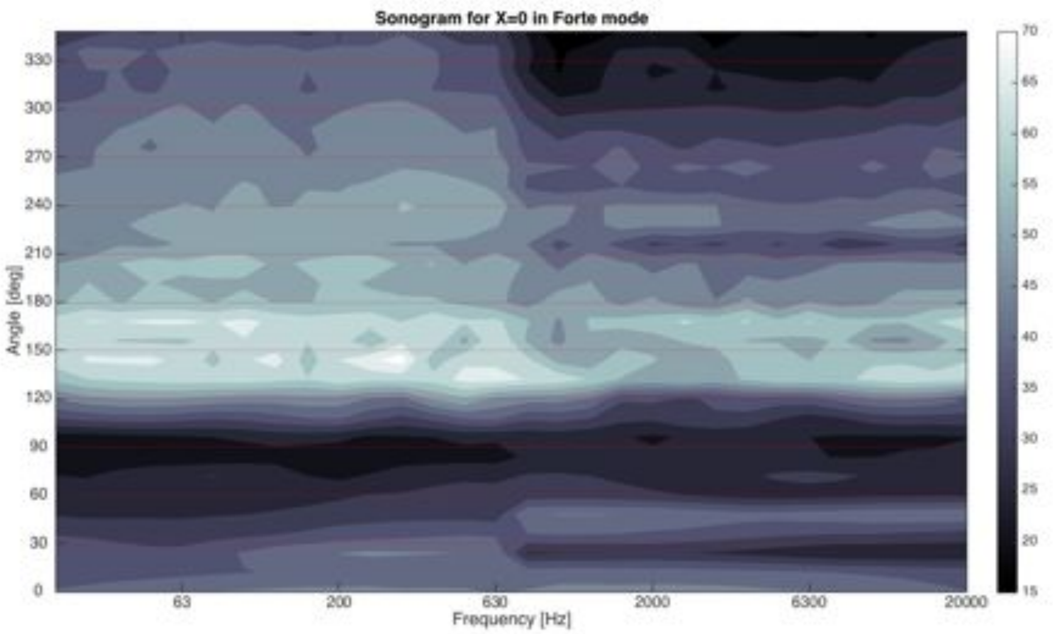

Figure 27. Sonogram for x=0 in Forte mode.

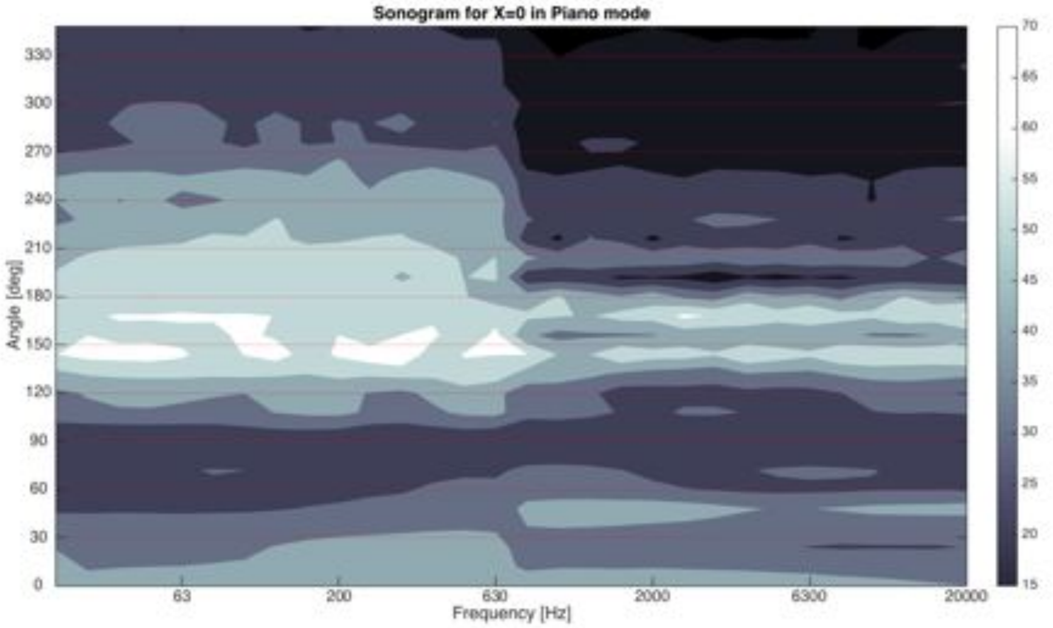

Figure 28. Sonogram for x=0 in Piano mode.

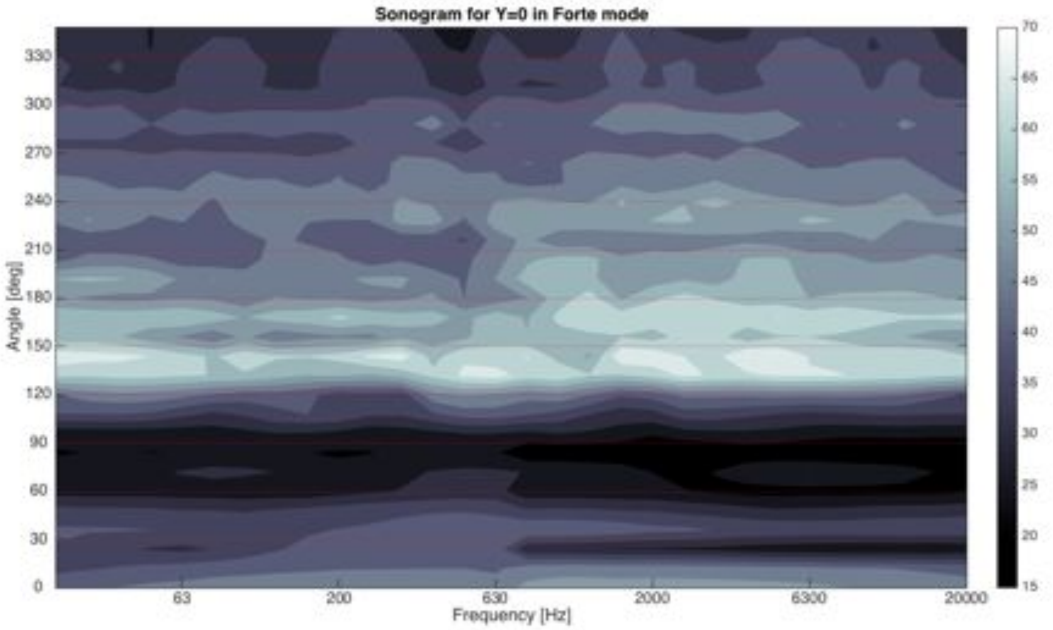

Figure 29. Sonogram for y=0 in Forte mode.

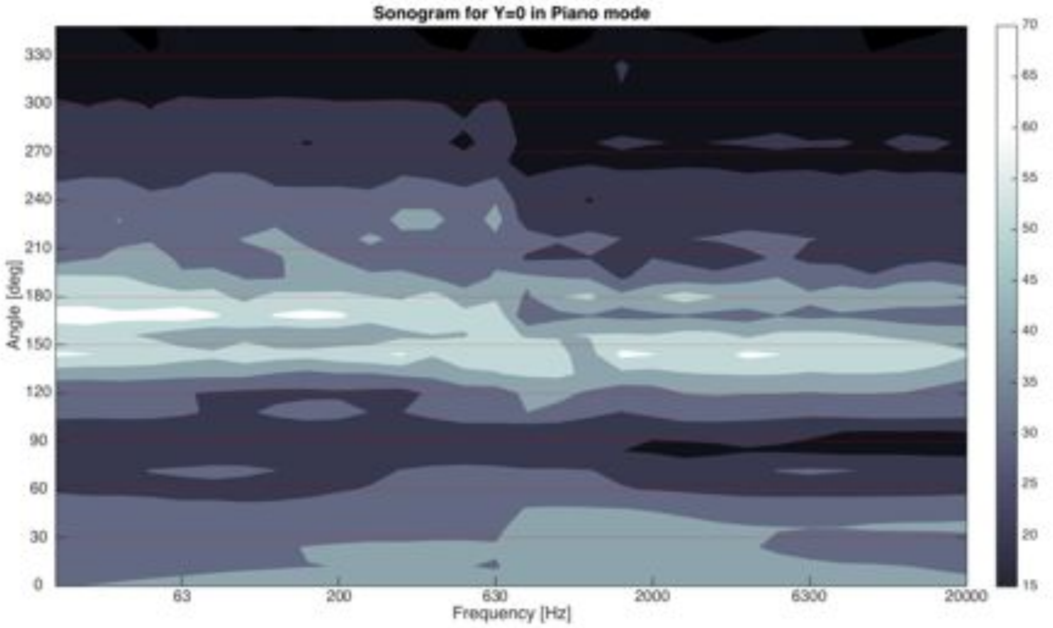

Figure 30. Sonogram for y=0 in Piano mode.

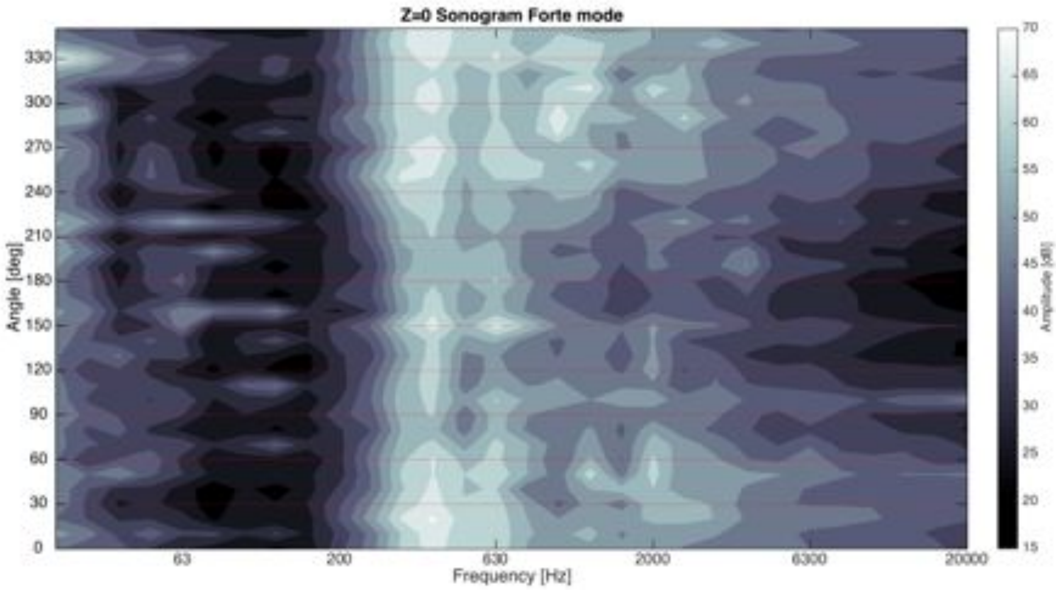

Figure 31. Sonogram for z=0 in Forte mode.

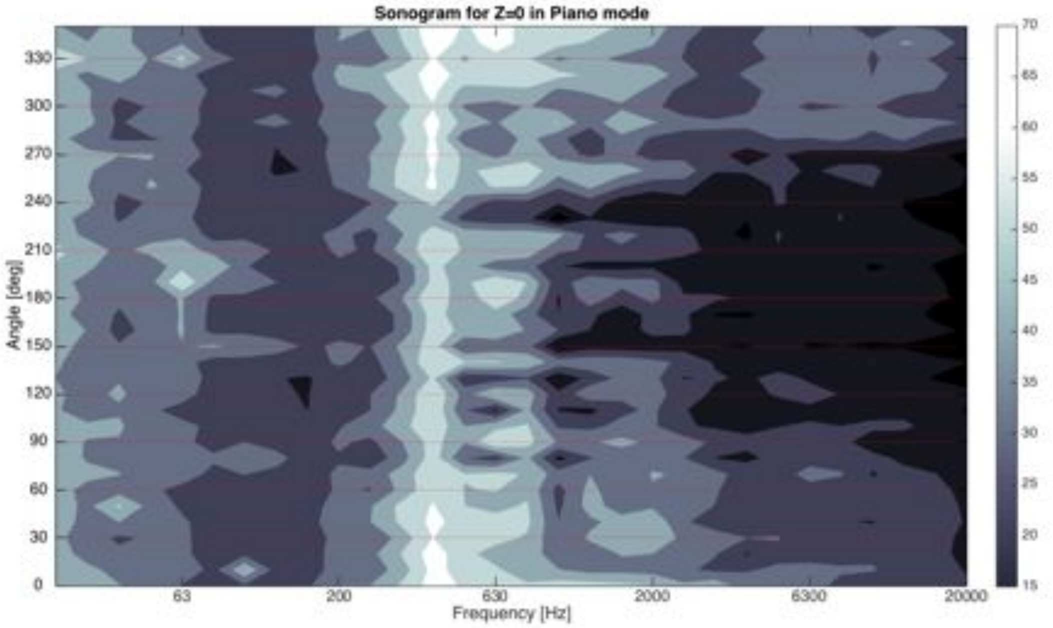

Figure 32. Sonogram for z=0 in Piano mode.

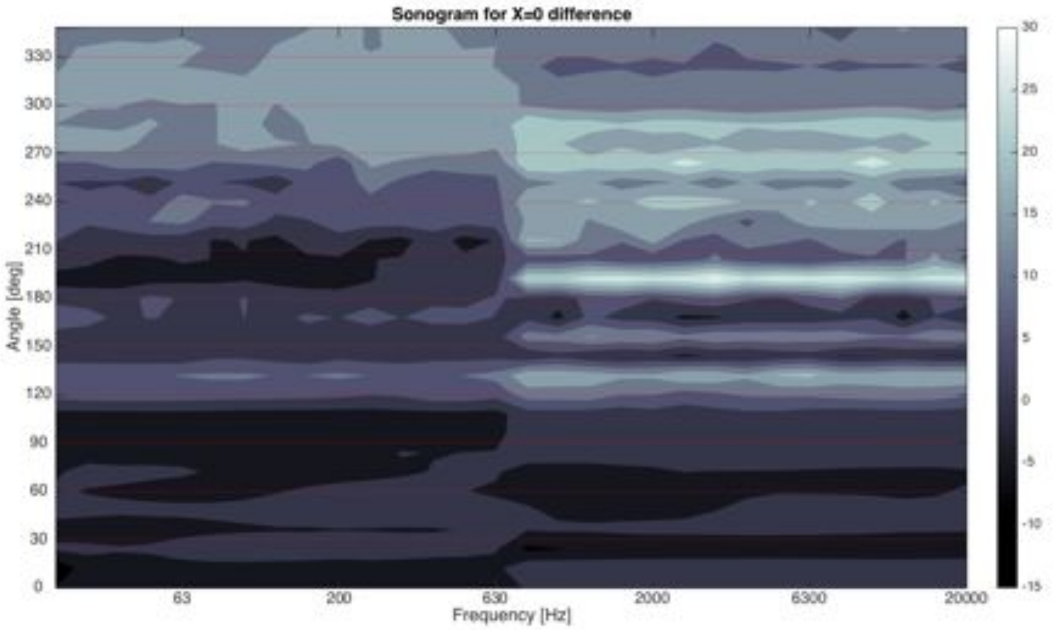

Figure 33. Sonogram difference for x=0.

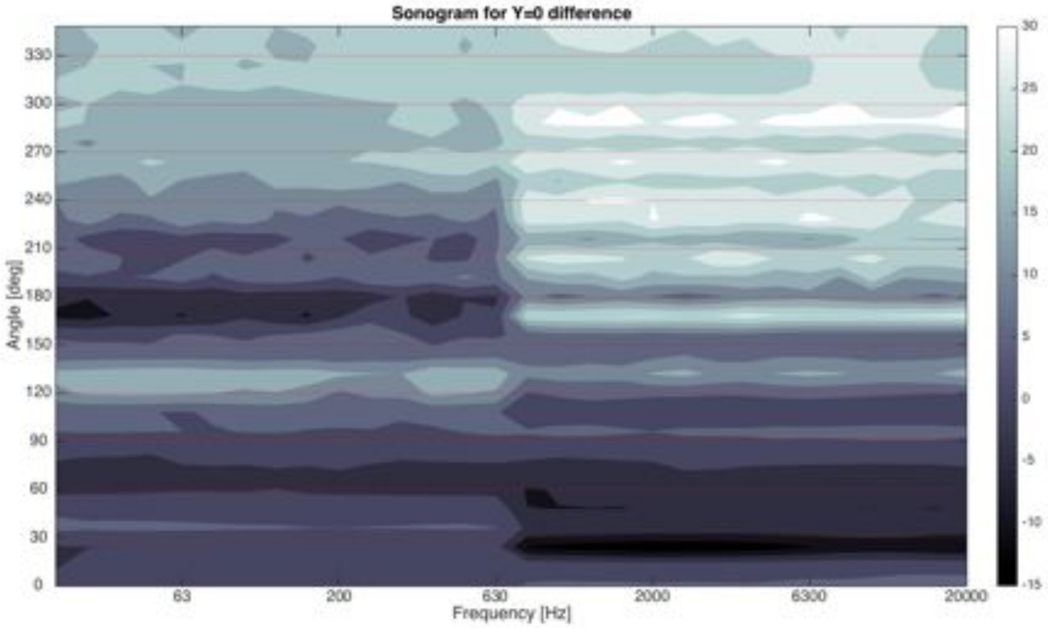

Figure 34. Sonogram difference for y =0.

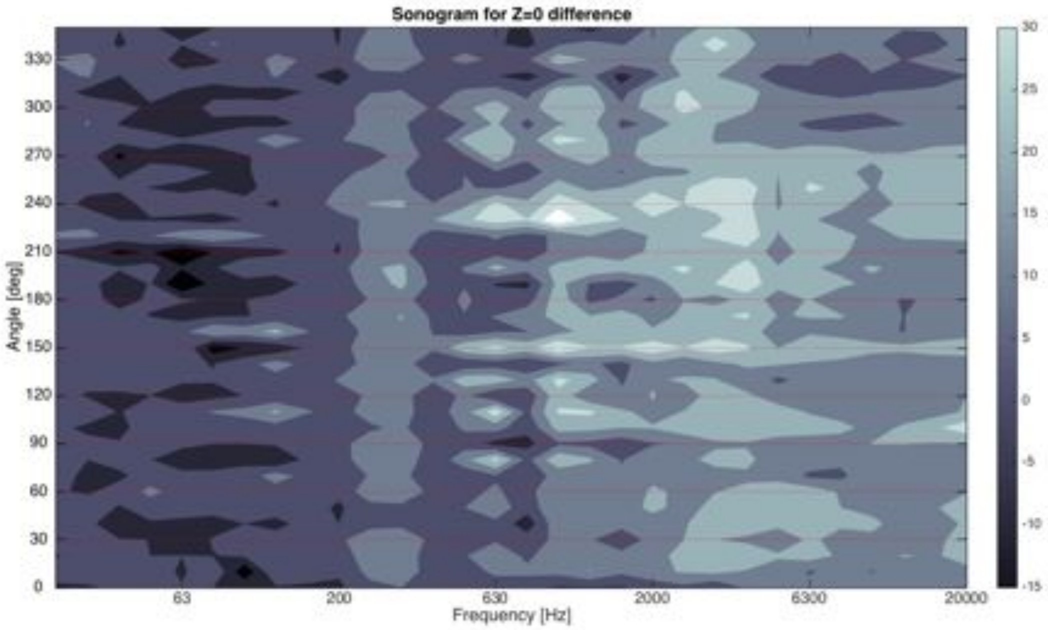

Figure 35. Sonogram difference for z=0.