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Design and construction of an omnidirectional sound source with inverse filtering approach for optimization

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A B S T R A C T

The aim of this study is to design an efficient omnidirectional point source whose analysis and design is also described here. The point source was designed with the help of MATLAB and SolidWorks software respectively for calculating the optimal dimensions. This point source is composed of a base in which the speaker is settle, and a cone that provides the omnidirectionality. Three different bases with three different cones were implemented and tested to determine which combination gives less reflection on rear part of cabinet. To enhance a flat response and true omnidirectionality, an Inverse Filtering Method will be introduced to the study. As a result, we observe that the point source is best suited with a cylindrical base and a 20 cm long cone. The radiation patterns showed omnidirectional results for frequencies lower than 15 kHz, and maximum deviation of 4 dB for 30 degrees.

Hardware name	*Omnidirectional Sound Source*
Subject area	• Engineering and Material Science
Hardware type	• Field measurements and sensors
Open Source License	*Open Source Hardware (OSHW) Definition 1.0*
Cost of Hardware	*$190 USD*
Source File Repository	*https://osf.io/rxgkd*

1. Hardware in context

Since ancient times the analysis of how sound behaves, when certain variables are manipulated has kept human kind interested. It is well known that ancient American cultures modified certain angles and geometries of their structures to create an acoustic disturbance of a palace or a chamber [1]. Nowadays before planning the construction of any kind of theatre of acoustic enclosure, an acoustical analysis must be performed [2]. This is done with help of an omnidirectional sound source, which are commonly an array of directional speakers, organized in a spherical way,

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so that sound is able to propagate evenly in all directions [3–4]. Other use of this kind of sources is to perform analysis of the ground, the acoustic reflections that come from the soil after being radiated by the sound source [5]. To show concentration of certain minerals or even soils in the ground [6], it can even be used to distinguish between different kinds of surfaces i.e. the fuel consumption in a car depending on the type of road [7]; or imperfections on certain pieces while a manufacturing process is performed. Omnidirectional sources are also widely used in the music industry, they are not only used for concerts as acoustical reinforcement, but they can also be used for any kind of reinforcement in locations such as conference rooms, lobbies at airports or shopping malls [8]. One benefit of using this design is that depending on the function and the operation the user wishes to give the source, it can be resized and the performance will not be disrupted. i.e., in the music industry you can enlarge all the generator's dimensions and enhance the low frequencies, or put it in a car and make it smaller and ensure it fits everywhere and enhance high frequencies [9].

The use of an omnidirectional sound source is limitless, depending on the needs of a physical space and the client's budget [10]. Some omnidirectional sound sources can be as expensive as some thousands of USD, acquiring them in developing countries can be tricky and time consuming. That is the reason why this paper presents a solution for a home built, professional and portable omnidirectional sound source.

As mentioned above, it can be established, as part of experimentation in acoustic engineering, which many experiments such as insulation problems, acoustic conditioning issues and especially characterization of materials, become efficient experiments when carried out under environmental conditions emulating real operating conditions [11]. For this, the ideal omnidirectional sources are a model whose emission characteristics of acoustic waves that propagate in all directions with the same energy are suitable for the generation of sound fields in enclosures where a diffuse sound field is needed inside the enclosures [12]. Therefore, omnidirectional sources are desirable in rooms where acoustic experiments are going to be carried out [13]. This is the motivation to generate this type of speakers, while experimenting with an original design with suitable materials and within reach for future experimentation.

2. Hardware and software description.

As mentioned before, six different pieces were 3D printed. Three different cones in length (20 cm, 25 cm and 30 cm) and three different bases (conical, cylindrical and trunked cone). Figure 1 shows an image of the finished cones, and Figure 2 shows an image of the finished bases. It is important to mention that these bases have a little hole for inserting a cable and connect the speaker with an amplifier; also, the speaker has already been adjusted and attached to the base with the screws. As these pieces were 3D printed, they needed the next steps to be developed to be fully compatible with each other:

Clean the imperfections of each piece created by the printer to support and allow it to be easily removed from the printing base.
Remove support material and define small parts such as internal ropes and external.
Paste the pieces of cones and bases to create the sources.
Fill imperfections with plastic sealer (Plaster)

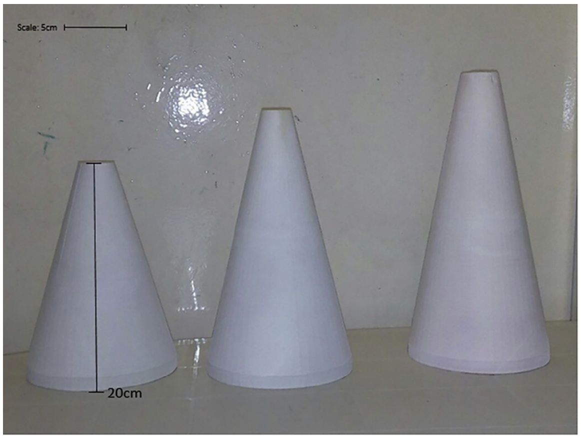

Fig. 1. Shows the three different cones glued using cyanoacrylate, for smoothing the surface, and the joints plaster was used as patching material, sanded with thin sand paper and painted ready for use.

Fig. 2. Show the three bases glued together with the speaker's base and the speaker joined. In the outer part of the base one plastic strip was placed for acoustical isolation.

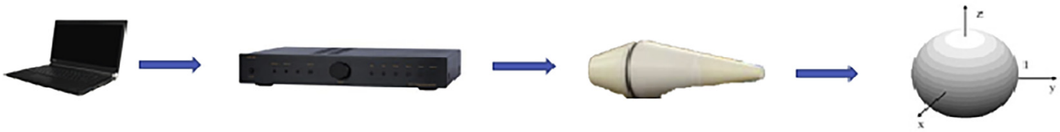

Fig. 3. Flow Diagram of how the signal is produced with all its elements.

Sand imperfections
Seal an approximate vacuum

If the user has some experience with printing in ABS plastic, he/she knows that some pieces should be glued together using acetone or any other polymer that can help in the process. Cavities of glued pieces should be filled and finally sanded.

For the implementation of printing, a 3D printer will be used, within our facilities at Tecnologico de Monterrey. Due to the size specifications, it was decided to use the CubePro printer since the base can print prototypes up to 30 cm × 30 cm. In order to start the process of transformation and calibration of parameters, an STL file must first be used as a base.

Once all pieces are printed one cone and one base must be attached with a special thread that has been already designed. Fig. 3 shows a flow diagram of the experimental setup. In the PC or laptop, the Inverse Filtering Technique is applied [14]. Moreover, a digital signal is produced and send to an audio amplifier. This audio amplifier may varies depending on how much power is needed to cover the completely physical area of study. After the digital signal is produced and amplified, it travels to the coaxial speaker and the digital signal is then transduced into an acoustical wave. As the speaker is attached to the base, the sound wave travels through the cone and at the end of it, the wave acquires omnidirectional properties of the field.

To simulate the approximate frequency response of the resonance box that will contain the selected speaker, WinISD software version 0.44 was used. This is a program that allows free and easy to make professional simulations based on the Thiele Small parameters of a speaker and at the same time on the physical characteristics of the soundboard, dimensions, vents, thickness, geometry, etc. [15–16].

Also, to be able to make an adequate decision about the optimal measurements that the source should have, the frequency response that in theory this geometry would have was simulated first in the Matlab program and Physically the cones and the bases used [17–18].

Finally, the radiation patterns obtained from the measurements from the source, going through the Inverse Filtering technique and later to time windowing, this analysis was developed using the Matlab software [14].

3. Design files Design Files Summary

Design file name	File type	Open source license	Location of the file
ConoXXcm.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
ConoXXcm.STL	STL file for 3D printing	Open Source Hardware (OSHW) Definition 1.0	Available with the article
BaseBocina.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseCil.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseBola.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseConoTrun.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseBocina.STL	STL file for 3D printing	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseCil.STL	STL file for 3D printing	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseBola.STL	STL file for 3D printing	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseConoTrun.STL	STL file for 3D printing	Open Source Hardware (OSHW) Definition 1.0	Available with the article
ConoXX Sólido1.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
ConoXX Sólido2.SDLPRT	Solidworks design file	Open Source Hardware (OSHW) Definition 1.0	Available with the article
Cono20cm.cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseBocina. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseCil. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseBola. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
baseConoTrun. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
ConoXX Sólido1. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
ConoXX Sólido2. Cubepro	3D cubepro File	Open Source Hardware (OSHW) Definition 1.0	Available with the article
BCI_CXX 3D	MatLab 3D Fig	Open Source Hardware (OSHW) Definition 1.0	Available with the article
BCO_CXX 3D	MatLab 3D Fig	Open Source Hardware (OSHW) Definition 1.0	Available with the article

ConoXXcm.SDLPRT: Solidworks file with the complete design ready for improvements or export to other formats of the 20-cm long cone
ConoXXcm.STL: File with the stereolithography information for 3D printing or any other computer-aided manufacturing process of the 20-cm long cone
BaseXXXXX.SDLPRT: Solidworks file with the complete design ready for improvements or export to other formats of the source.
baseXXXXX.STL: File with the stereolithography information for 3D printing or any other computer-aided manufacturing process of the piece that holds the speaker, this piece must be attached to the base of the source.
baseConoTrun.STL: File with the stereolithography information for 3D printing or any other computer-aided manufacturing process of the truncated cone base
ConoXX Sólido1.SDLPRT: Solidworks file with the complete design ready for improvements or export to other formats of the 25-cm cone's first part.

ConoXX Sólido2.SDLPRT: Solidworks file with the complete design ready for improvements or export to other formats of the 25-cm cone's second part.
ConoXX Sólido1.STL: File with the stereolithography information for 3D printing or any other computer-aided manufacturing process of the 30-cm cone's first part. This cone is divided in 2 different pieces because the biggest size for this printer is 20 cm. Once this file is printed, it must be attached to the "cono30 Solido2.STL"
ConoXX Sólido2.STL: File with the stereolithography information for 3D printing or any other computer-aided manufacturing process of the30 cm cone's second part. This cone is divided in 2 different pieces because the biggest size for this printer is 20 cm. Once this file is printed, it must be attached to the "cono30 Solido1.STL"
Cono20cm.cubepro: This is the file that must be introduced into a CubePro trio 3D printer. This file contains all the information about the Layer resolution (200 μm), print strength (almost solid) and print pattern (diamonds) these parameters are calculated for a strong hardware but not too difficult for the printer to make. It doesn't consume a lot of material. This for the 20-cm cone
baseXXXXXXX.Cubepro: This is the file that must be introduced into a CubePro trio 3D printer. This file contains all the information about the Layer resolution (200um), print strength (almost solid) and print pattern (diamonds) these parameters are calculated for a strong hardware but not too difficult for the printer to make. It doesn't consume a lot of material. This for the base where the speaker is attached.
ConoXXSólido1. Cubepro: This is the file that must be introduced into a CubePro trio 3D printer. This file contains all the information about the Layer resolution (200um), print strength (almost solid) and print pattern (diamonds) these parameters are calculated for a strong hardware but not too difficult for the printer to make. It doesn't consume a lot of material. This for the first part of the 25-cm cone. Once printed this part must be attached or glued to the cono25 solido2
ConoXXSólido2. Cubepro: This is the file that must be introduced into a CubePro trio 3D printer. This file contains all the information about the Layer resolution (200um), print strength (almost solid) and print pattern (diamonds) these parameters are calculated for a strong hardware but not too difficult for the printer to make. It doesn't consume a lot of material. This for the second part of the 25-cm cone. Once printed this part must be attached or glued to the cono25 solido1
BCI_CXX3D: 3D representation of 180° response of the source showing the power of the signal with different colors, the angle of dispersion and the frequencies analyzed of a 20 cm cone attached to a cylindrical base
BCO_C20 3D: 3D representation of 180° response of the source showing the power of the signal with different colors, the angle of dispersion and the frequencies analyzed of a 20 cm cone attached to a conical base
BR_C20 3D: 3D representation of 180° response of the source showing the power of the signal with different colors, the angle of dispersion and the frequencies analyzed of a 20 cm cone attached to a round base
BR_SC 3D: 3D representation of 180° response of the source showing the power of the signal with different colors, the angle of dispersion and the frequencies analyzed of cone-less source and round base

Matlab code in order to calculate the inverse filter

```
%%Matlab code in order to calculate the inverse filtering for the omnidirectional point source
%% David Ibarra ITESM, 2018
ri; % ri is the impulse response previous measured between point source-microphone
n = length(ri);
n2 = round(n/2);
fs=96000; %Sample frequency
df = fs/length(data);
dt = 1/fs;
[m0,i0] = max(ri);
MFT=abs(fft(ri,n));
FaFT=angle(fft(ri,n));
m = max(MFT);
%Parameters for phase 0 and amplitude cosine
A =1;
g =0.1;
finf = 80;
fsup = 18000;
fc=0.5*(finf+fsup);
fbw=(fsup-finf);
fi=round(fc-0.5*fbw);
ff=round(fc+0.5*fbw);
idout=[zeros(fi-1,1)' A*(cos(pi*((fi:ff)-fc)/fbw)).^g zeros(n-ff,1)']';
[m1,i1]=max(idout);
i2=i1-i0;
idout=rnge(idout,i2)*m0/m1;
```

```
IDOUTMOD=abs(fft(idout));
IDOUTFAS=angle(fft(idout));
pm=0.01*p*m;
MFTp=MFT+pm;
%Minimum phase
IDINMOD=IDOUTMOD./MFTp;
IDINPHS=IDOUTFAS-FaFT;
idin=real(ifft(IDINMOD.*exp(1i*IDINPHS)));
idin=idin';
%Normalization
m2=max(abs(idin));
idin=idin/m2;
```

4. Bill of Materials

Designator	Component	Number	Cost per unit-currency	Total cost-currency	Source of materials	Material type
Cono20cm	Cone	1	70 USD	70 USD	https://www.3dmarket.mx/filamentos-para-impresora-3d/	ABS Plastic
baseBocina	Speaker's Base	1	20 USD	20 USD	https://www.3dmarket.mx/filamentos-para-impresora-3d/	ABS Plastic
baseCil	Source's Base	1	40 USD	40 USD	https://www.3dmarket.mx/filamentos-para-impresora-3d/	ABS Plastic
	Speaker	1	30 USD	30 USD	http://www.bassfacecaraudio.co.uk/products/coaxial-component-speakers	Aluminum

4.1. Build Instructions

1. Using an appropriate 3D printing, print all the desired or needed pieces of the cone. As not all printers can print large pieces, sometimes it is needed glue or attach the pieces so the cone is complete. In this document and because of the characteristics of the 3D printer, certain cones were divided in two different pieces, CubePro trio 3D printer was the one used, and it could only print figures of $20 \times 20 \times 20$ cm. If the user uses another printer, then this limitation should be taken in account. Each cone has printed in two different pieces and glued together using polymers (cyanoacrylate and acetone).
2. Using the provided STL file and a 3D printer, print the speaker's base and the desired source's base. Please be aware that for each printed base, one "*base bocina*" file must be printed, this piece is where the speaker is going to be placed.
3. Glue or attach the speaker's base with the source's base. For this project, both bases were glued together using polymers (cyanoacrylate and acetone). It is important to be careful when using acetone and certain plastics. These pieces were printed using ABS plastic, acetone melts down this specific plastic when it is applied in quantities bigger than five drops per cm^2.
4. In order to set the speaker, first attach the speaker's wire to the speaker; pass the wire through the whole located in the base, so it can have a connection with the amplifier. Seal that exit with any glue in case the wire is too thin compared to the whole's diameter. Place the speaker on the base and use the speaker's screws to attach the base with the speaker and make sure they fit together perfectly. Once attached all pieces one base should be joined with a cone. It is important to make sure there is no air leak between the joined parts.
5. To apply the digital processor, the Inverse Filter should be compiled in MATLAB software and an audio cable (cable jack 3.5 to RCA) should be connected between an amplifier and the computer, the amplifier's power may vary according to the physical space that must be covered.
6. Use a jack 3.5 cable on one end and trim the other end of the cable, the trimmed part of the cable will be attached to the speaker and the end that has a 3.5 jack will plug in an analog output port of the amplifier.
7. There is always the possibility to use another speaker and replace the one that was suggested with a coaxial passive speaker.
8. As seen in the "design files summary" part, the Cubepro files are included, this files are important because this orientation is the one who takes less time and also the one which consumes the less material. The final user is very free to print its pieces with whichever orientation he prefers, nevertheless there are certain orientations, which will require more support material and which will consume more time.

5. Operation Instructions

The construction of the source was finally done with plastic. This because, a 3D printer was going to be used. The advantages of using this kind of printer are:

- Using ecofriendly materials or recycled plastics, the source's production will not harm the environment and industrial wastes will not take place.
- As it is made of simple plastic, its price will be cheaper when compared to a design made of aluminum or any other metal.
- Any person who has access to a 3D printer will be able to produce its own source and they will not need to invest in transportation or taxes.

For printing the source, a Cube Pro Trio 3D Printer was used, together with its software. White and red ABS plastic was used for this study because of accessibility problems. Each piece was divided into two different parts so that they could fit the printer. After they were done printing, each piece was glued together with its partner using two different kinds of polymers, acetone and later on cyanoacrylate. Once the pieces were rock solid they were sanded so all imperfections were cleaned and both pieces could fit perfectly. This is important because otherwise, sound could escape from any other place apart from the opening of the cone's top, causing erroneous measurements. Use these considerations: 1) *Handle with care*. 2) Do not make the source wet or put it into water. 3) Once assembled do not open the source when the source is generating sound. 4) Do not connect the source to a power amplifier that might damage the speaker.

6. Validation and characterization

In order to perform the measurement of the impulse and frequency responses and to plot the radiation pattern, these steps were followed; each of the sources' combinations were assembled and mounted in an electrical turntable such as it can be appreciated in Figs. 4 and 5. For analyzing the sources' patter and operating the turntable, it was plugged into a computer and a specialized software used to test the radiation patterns of telecommunication's antennas. This software allows us to move the turntable in specific steps according to the methodology of the study. In this case, the minimum spin of the dish was 0.2°, which gives us a precision of 1800 individual steps for competing one whole turn (360°). Using one single key on the keyboard the turntable spin and that way the experiment was performed. For this study, each measurement was taken every 5°. The Mechatronic Engineering department at Tecnologico de Monterrey provided this software and hardware.

Fig. 4. Sound source mounted on the turntable.

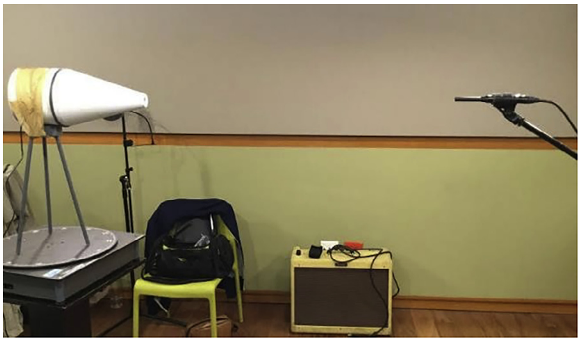

Fig. 5. Example of how the measurements were taken.

Inverse filtering technique is a method to offset all acoustic resonances caused by the walls of the cone while the acoustic wave travels through the interior or the source. All errors caused by reflections are treated with this method. For the calibration and correct implementation the length of the cone and the acoustic properties of the material were taken into account. Once every input was analyzed, what the inverse filter technique does, is first record the response of the source with all the interferences and sound abnormalities caused by the cone that data is processed and analyzed. According to the results, the inverse filter is calibrated and adjusted for this specific source. This specific calibration is the reason why the efficiency of the source does not depend on the material used to build it.

The inverse filtering technique implies to convolve the driving voltage to the loudspeaker with the inverse filter of the loudspeaker–microphone impulse response [14]. The point source–microphone system can be modeled as a linear filter. If $h(t)$ is the impulse response of the point source–microphone system, and its Fourier transform is: $H(f) = H_{poinsource}(f) + H_{amplifier}(f) + H_{microphone}(f)$. When the loudspeaker is driven by a conventional voltage, $x_c(t)$, the microphone receives a conventional waveform, $y_c(t)$, such as

$$Y_c(f) = H(f)X_c(f) \tag{1}$$

where $X_c(f)$ and $Y_c(f)$ are the Fourier transforms of the input and output signals, correspondingly. Instead of driving the loudspeaker with a conventional voltage and wait for its response, let us prescribe the shape of the radiated spectrum received by the microphone, $Y_s(f)$, and calculate the voltage which should drive the loudspeaker, $X_s(f)$. According to the linear system theory [14], this should be

$$X_s(f) = \frac{Y_s(f)}{H(f)} \tag{2}$$

The electrical signal which should drive the point source with a positive constant, p, must be added as a regularization. Where IFT^{-1} stands for inverse Fourier transform:

$$x_s(t) = IFT^{-1}\left[Y_s(f)\frac{H*(f)}{|H(f)|^2 + p^2}\right] \tag{3}$$

The MLS signal was measured each 5 degrees. After all measurements were done, an Inverse Filter was applied and also a window of time, and a correction factor. The Matlab code is sown in Section 3. This last one was necessary because of the different positions of the speaker when the turntable spins, the 1-meter distance between the speaker and the microphone was not always constant, as the turntable spins this distance changes too. In Figs. 6 and 7 polar radiation can be seen.

It is important to clarify that this test was not performed inside an anechoic room; because of this, perfect results were not achieved. Nevertheless, the anechoic room was not used, a professional recording studio was used for this study. Some precautions were taken into account, such as having acoustic isolators on the walls and on the floor. Results shown in this paper were ameliorated. When analyzing the generated sound wave, only a small time window was taken into account, for this study only the signal generated in the time interval between the sound source and the microphone was analyzed. The rest of the signal was not taken into account because of reflections caused by nearby objects or unprotected walls.

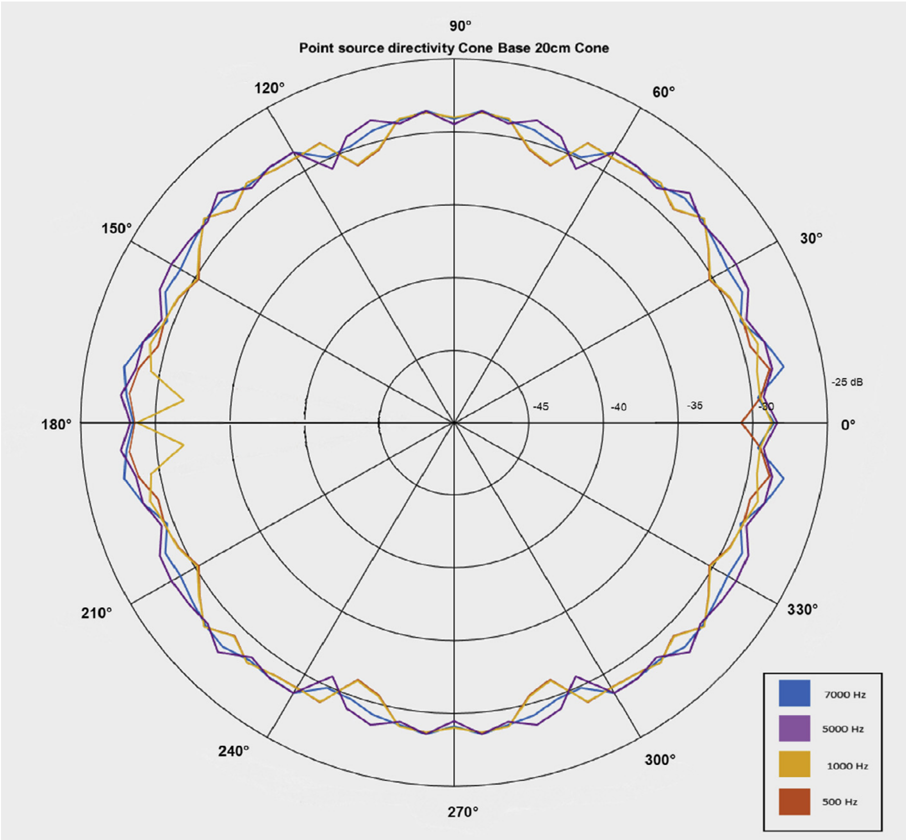

Fig. 6. Radiation pattern of the point source using a 20 cm cone together with a cylindrical base. Different frequencies are represented with different colors (500, 1000, 5000 and 7000 Hz) orange, yellow, purple and blue respectively.

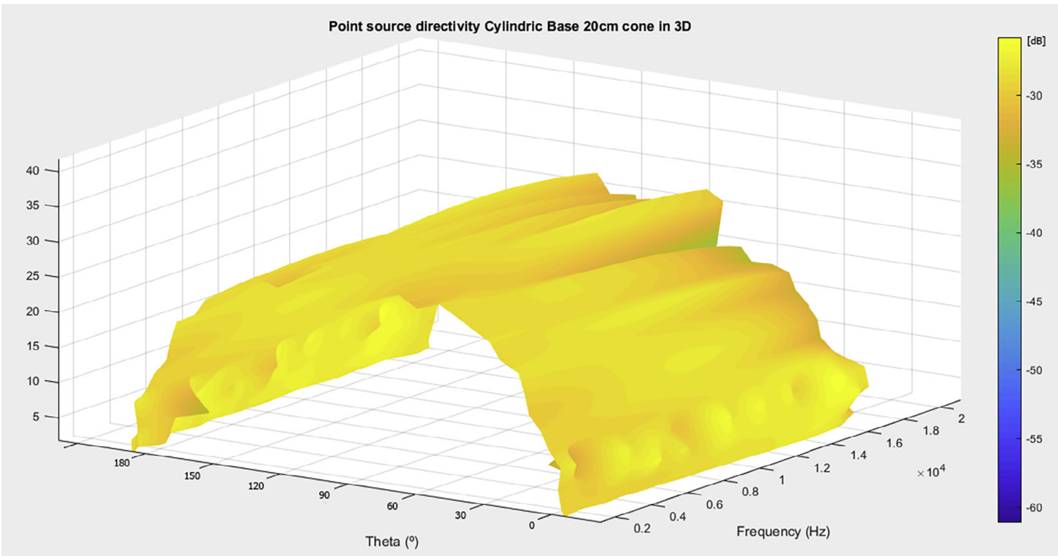

Fig. 7. 3D representation of a 180° radiation pattern produced by a point source composed by a 20 cm cone and a cylindrical base. Signal's power in dBs is represented by different colors; x-axis shows different frequencies that were analyzed throughout the project while y-axis represents the angle in degrees. Z-axis is only a relative scale for power representation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ohx.2018.e00033.

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