Low-cost and easily implemented anechoic acoustic chambers

Cámaras anecoicas acústicas de bajo costo y fácil implementación

Alejandro Orrego González[1], Joao Luis Ealo Cuello[1], Jhon Fernando Pazos Ospina[2]
[1] *Escuela de Ingeniería Mecánica, Universidad del Valle - Sede Cali, Cali, Colombia.*
[3]*Facultad Escuela Militar de Aviación Marco Fidel Suarez - Fuerza Aérea, Cali, Colombia.*
alejandro.orrego@correounivalle.edu.co
joao.ealo@correounivalle.edu.co
jhonfpazos@gmail.com

***Resumen*— En este trabajo se presenta el diseño, construcción y evaluación de una cámara anecoica de bajo costo usando materiales provistos por el mercado local; tales como: espuma de poliuretano, tubos de acero, fibra de vidrio, placas de fibrocemento, placas de madera aglomerada, etc. La cámara posee dimensiones de trabajo de 1,94 m de largo x 1,91 m de ancho x 1,84 m de alto y frecuencia de corte nominal de 400 Hz, a partir de la cual la cámara recrea condiciones de espacio al aire libre en cuanto a ondas sonoras se refiere. Pudo constatarse que la cámara cumple con la desviación máxima permitida de la ley del inverso cuadrado según la norma ISO 3745. El desarrollo de este tipo de proyectos es de vital importancia para la evolución tecnológica de países emergentes, ya que estimula la actividad de los investigadores y da posibilidades a la industria local para el desarrollo de procesos y productos en temas relacionados con la Acústica, temática poco desarrollada en países en vía de desarrollo.**

***Palabras clave*— cámara anecoica, campo libre, ley del inverso cuadrado, frecuencia de corte, norma ISO 3745.**

Abstract— In this paper, the design, construction and verification of a low-cost and easy-to-install anechoic chamber are described. The chamber is constructed with affordable, local materials. The quality, according to the deviation from the inverse square law, complies with ISO 3745. The working dimensions of the chamber are 1.94 m long x 1.91 m wide x 1.84 m high. The nominal cutoff frequency is 400 Hz. The cost per square meter of the effective finished volume is 200 USD. With this design, small- and medium-sized enterprises are able to build anechoic chambers with a small investment, adding value to their products through characterization and subsequent mitigation, conditioning or amplification, as necessary, of emitted sound or noise. This study also contributes to the development and appropriation of knowledge in acoustics, a branch of physics of emerging importance in developing countries.

***Key Word* — anechoic chamber, acoustics, low cost, free field, inverse square law, cutoff frequency, ISO 3745.**

I. NTRODUCTION

An anechoic chamber is an enclosure designed to recreate free field conditions. This type of enclosure has been implemented since the 1950s as a controlled environment for research in the field of acoustics [1]. In anechoic chambers, acoustic characterization of all types of sound sources and receivers, such as machinery, home appliances [2], audio sources [3], automobiles , aircraft [4], microphones, and others, is performed [5]. Anechoic chambers are also used to investigate the relation of sound to disease in humans [6], among other research areas. Research centers, such as the National Aeronautics and Space Administration (NASA, USA) [7], the University of Salford (England) [8], the Western Michigan University (USA) [8] and the Universidad Nacional Autónoma de México (UNAM, Mexico) [9], and some of the most prestigious companies worldwide, such as BMW, Whirlpool, and Bosch, employ anechoic chambers during the research, design and characterization of their products.

In much of South America, including Colombia, acoustics, as the branch of physics that studies the propagation of mechanical waves through materials, has not been well studied. As a result, there is a high degree of informality in the decision-making process in companies and institutions when faced with acoustics problems. Companies are restricted to importing technologies or outsourcing characterization tests, depending on their requirements. However, little is invested in the development of basic acoustics knowledge, new products or processes. In Colombia, for example, there is no known record of the existence of a qualified acoustic anechoic chamber providing services, or having the ability to provide services, to national companies in the development or improvement of their products. Therefore, companies must request such services of foreign entities, where the cost of each acoustic characterization of an acoustical

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absorber material can easily exceed several thousand dollars. It is well known that the domestic industry is experiencing an increasing demand in a globalized market, which seeks standardized products in all aspects. With respect to noise, low-emission products are sought; therefore, it is vital to have an anechoic chamber where products can be characterized and/or improved.

In Colombia, two anechoic chambers have been reported: one in Bogotá, which is a scale prototype of a possible anechoic chamber of a larger size [1], and a semi-anechoic chamber at the Universidad Nacional de Medellín in the Applied Technologies Research Group (ATRG), which has been used for noise characterization from refrigerators [9].

Considering the lack of locally available anechoic chambers, the aim of this study is to promote the construction and development of anechoic chambers in Colombia. The design, construction and preliminary verification of an anechoic chamber are described in this paper. From the beginning, the work had two important requirements: 1. the chamber must be inexpensive and therefore accessible to small- and medium-sized companies, and 2. the materials used in construction should be easy to obtain locally.

The basic principles for the design of an anechoic chamber for acoustic purposes are presented first. Subsequently, the determination of the chamber size is described, and building materials are proposed. Computer simulation results are used to finalize the proposed design. Finally, the details of the built chamber and the results of the verification are presented. These results indicate that it is possible to achieve an enclosure of outstanding quality that emulates free-field conditions with little capital investment.

II. THEORETICAL FRAMEWORK

An anechoic chamber is an enclosure consisting primarily of insulating walls, anechoic wedges, support grids, and elastic material for the insulation of structurally transmitted noise. Figure 1 illustrates the basic guidelines applied to the design and construction of an anechoic chamber.

The sizing of the anechoic chamber is one of the most important steps, requiring the greatest care. Equations (1), (2) and (3) define the internal dimensions of the anechoic chamber (h is the height, w is the width and l is the length) as follows [5]:

$$h = a + 2a + \frac{\lambda}{2} + l_c \tag{1}$$

$$w = a + 4a + \frac{\lambda}{2} + 2l_c \tag{2}$$

$$l = a + 2a + \frac{\lambda}{2} + 2l_c \tag{3}$$

where a is the maximum dimension of the sound source to be characterized within the enclosure, $2a$ is the distance between the microphone and the sound source, λ is the wavelength at the cutoff frequency of the anechoic chamber (400 Hz in this case) and l_c is the minimum distance from the source to one of the anechoic walls ($l_c \geq \lambda/4$).

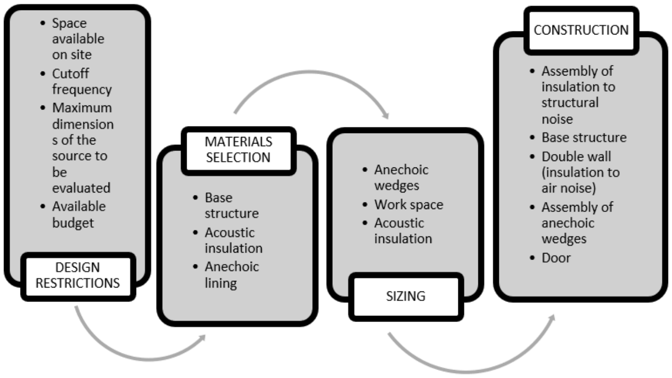

Figure 1. Diagram of design and construction process of the anechoic chamber. Source: The authors.

In addition, the resonances of the anechoic chamber should not be linked to the modes of vibration of the enclosure; i.e., they should not be too close to one another to minimize constructive interference that would negatively affect the performance of the chamber. The vibration modes of a parallelepiped enclosure are described by equation (4) [10]:

$$f_{k,m,n} = \frac{c}{2}\sqrt{(\frac{k}{L_x})^2 + (\frac{m}{L_y})^2 + (\frac{n}{L_z})^2} \tag{4}$$

Where L_x, L_y, L_z are the inner dimensions of the chamber in meters and k, m, n are integer values (0, 1, 2, 3…, n). The designation of each mode is given according to k, m, n. The axial modes of vibration contain more energy than the tangential and oblique modes of vibration because they occur by reflection on fewer surfaces [10][11]. As the number of reflections increases, the amount of energy dissipated on the walls and in the medium through which the wave travels increases. Therefore, when determining the final dimensions of the chamber, the density of resonance frequencies should be as low as possible in accordance with the space available, reducing the possible superposition of eigenmodes of the enclosure.

The external dimensions of the anechoic chamber depend on the size and geometry of the structures that comprise the lining and the thickness of the wall insulation. The dimensions of the lining are linked to the wavelength at the designed cutoff frequency (400 Hz). There are different types of anechoic lining structures; however, the geometries most commonly used are wedges. The parts of such anechoic wedge are shown in Figure 2. The total length (D) must be a quarter of the wavelength at the cutoff frequency. Generally, in anechoic absorbers type wedges, the base (L2) is approximately 1/6D, L1 is approximately 5/6D and the air space (L3) is approximately 1/8D. The recommended angle θ is approximately 30°. Much lower angles excessively increase the number of required wedges, and much greater angles reduce the total absorption area. The angle θ defines the height of the wedge base (r) [5][12][13][14].

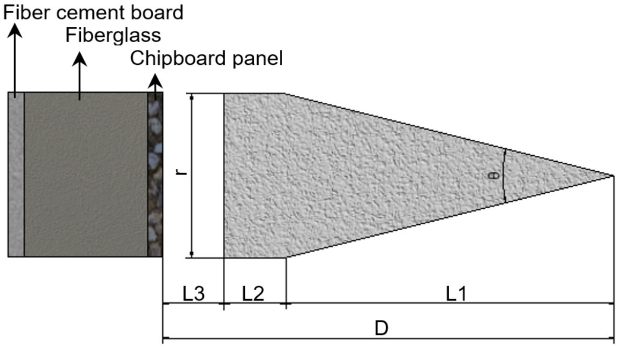

Figure 2. Anechoic wedge with air space and posterior double wall. Source: The authors.

The anechoic chamber must be isolated from external noises that might disturb the measurements to be performed in the chamber. An efficient strategy for airborne noise insulation utilizes double walls with absorbent material fill. Equation (5) is used to calculate the insulation R for this type of double wall [15]:

$$R = 20 * log\left(\frac{m_1*m_2*d}{2*\rho^2*c^3} * (2\pi)^3 * f^3\right) \quad (5)$$

where ρ is the density of the absorbent material separating the walls, c is the speed of sound in air, m_1 and m_2 are the masses of the walls, d is the separation between the walls and f is the cutoff frequency for the operation of the insulation. Insulation from flanking noise, i.e., the noise from outside that is transmitted through the structure supporting the chamber, is minimized by supporting the structure by elastic material, such as neoprene, natural rubber, or hangers [15][16][17].

In the early twentieth century, Wallace Sabine developed an expression to predict the reverberation time in an enclosed area. This parameter is the time between the first emission of a sound and when it drops 60 dB from its initial value [18]. The RT within an anechoic chamber has been measured at 30 ms [1]. Lower values in the same order the magnitude have also been reported. The expression for the RT is as follows:

$$\mathrm{RT} = \frac{0.161\mathrm{V}}{A\alpha} \quad (6)$$

where V is the volume of the room in m^3, A is the area of the absorbing surface in m^2 and α is the coefficient of absorption of the surface. Other authors have developed their own expressions for calculating the reverberation time (Eyring, Millintong and Fitzroy) [19].

Porous or fibrous materials, such as polyurethane foams (porous) or rockwool (fibrous), and fiberglass are used as absorber materials. These materials are used because they have sound absorption coefficients greater than 0.9 in the audible frequency range (20 Hz to 20 kHz). That is, more than 90% of the sound energy incident on these materials is absorbed within their structures by transforming the sound energy into heat as a result of the friction of the air particles inside the pores of the absorbent material. A device used to measure the sound absorption coefficient of materials is known as a Kundt tube.

III. MATERIALS AND METHODS

The design and construction of the anechoic chamber integrate a series of processes that focus on the same goal, which is to achieve conditions of open-air space within an enclosure. In view of this, the enclosure must be insulated from external noise, and sound generated internally must be absorbed by the inner walls. In addition to the design and construction process, an evaluation of the anechoic chamber is required.

A. Lining structure

The methodology used in this work for the development of anechoic wedges comprises three steps: 1. the selection of the material for manufacturing the wedges; 2. the evaluation of the absorption coefficient of the selected material; and 3. the verification of the design, using a finite element software to evaluate the acoustic response of the material with the stipulated geometry.

For this study, flexible open-cell polyurethane was selected as the material for manufacturing the anechoic wedges because it is innocuous, it has a high sound absorption coefficient [20], is an easy material to obtain on the local market and is easy to handle. It is also simple to fabricate an anechoic wedge from flexible open-cell polyurethane. Three different flexible open-cell polyurethane foams of different densities were evaluated, i.e., D40 (40 kg/m3), D30 (30 kg/m3) and Spumflex (Espumas Flexibles de Colombia S.A.S.) (18kg/m3), to find the material with the largest sound absorption coefficient. A Kundt tube was used to measure the sound absorption coefficients of specimens 45 mm in diameter and 50 mm and 75 mm in thickness. Furthermore, within the design stage of the wedges, a finite element model was developed using the acoustics module of COMSOL Multiphysics$^{\mathrm{TM}}$ to simulate the acoustic behavior of an array of 4 anechoic wedges and to estimate the sound pressure reflected by the wedges. The configuration of the model conditions is shown in Figure 3. The model used 16 elements per wavelength. The scattered field formulation was used.

B. Construction

The materials used in the construction of the anechoic chamber were all purchased on the local market, easily accessible and commonly used in construction. The materials included steel tubes with a square profile of 6 cm x 6 cm and a thickness of 2.5 mm, fiberglass, flexible open-cell polyurethane foam with a density of 40 kg/m3, thick fiber cement sheets with a thickness of 8 mm, chipboard, wooden slats with a profile of 1 in x 2 in, assembly screws, silicone and 1.9 m x 1.9 m stainless steel mesh.

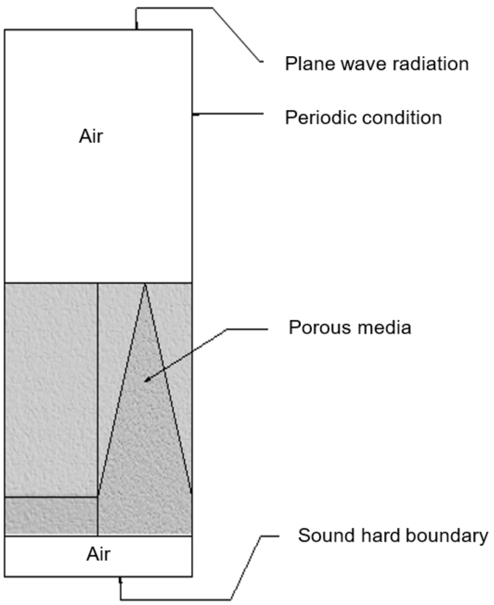

Figure 3. Boundary and material conditions in the simulation model of anechoic wedges. Source: The authors.

The frame was built first. The tubes were filled with foam and then arc welded. Subsequently, fiber cement external walls were assembled, and the chipboard internal walls were fastened to the welded tube frame. Fiberglass was placed between the walls to complete the construction of the double wall insulation for airborne noise. On the inner walls, wooden slats were fastened to the chipboard panels with assembly screws. The anechoic wedges were glued to the wooden slats with polychloroprene glue. A model of the assembly process is shown in Figure 4. To maximize the acoustic absorption area, the tips of two adjacent wedges are located forming an angle of 90 degrees.

Final external dimensions of the anechoic chamber are 2.44 m wide x 2.44 m long and 2.34 m high. The internal dimensions are 2.34 m wide x 2.37 m long x 2 27 m high. Regarding the work space, dimensions are 1.94 m long x 1.91 m wide x 1.84 m high.

C. Evaluation of the anechoic chamber

A microphone is placed 1 m from the source, and measurements are taken at 9 points on a diagonal from the first point, spaced 10 cm from each other, in the direction indicated by the black arrow in Figure 5.

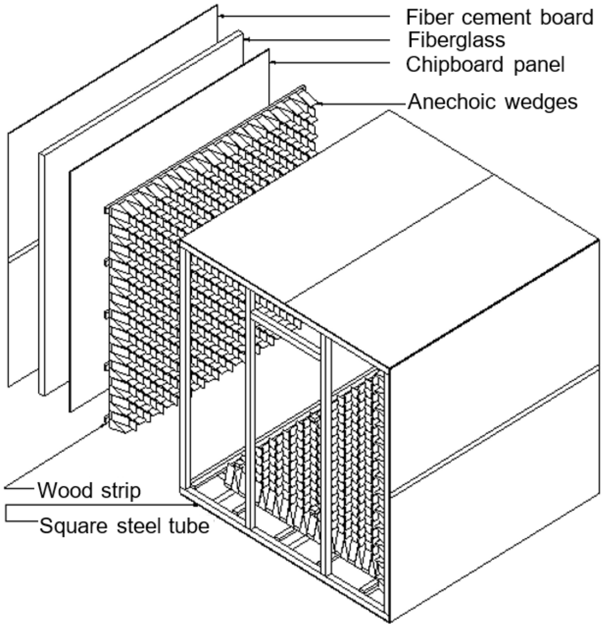

Figure 4. Anechoic chamber assembly. Source: The authors.

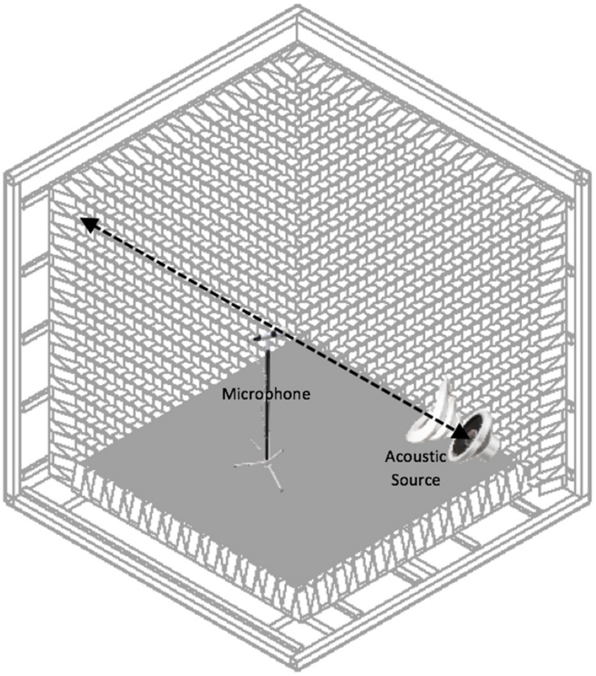

Figure 5. Measurement direction with source and microphone initial position into the anechoic chamber. Source: The authors.

To qualify an anechoic chamber based on sound pressure levels (SPLs) measured at the specified positions, the theoretical SPLs must be estimated. These are determined for each measurement point using the following equation [13]:

$$L_p(r) = 20log\left[\frac{a}{r-r_0}\right] \tag{7}$$

where r is the distance from the source to the measurement position,

$$a = \frac{\left(\sum_{i=1}^{N} r_i\right)^2 - N\sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i} \tag{8}$$

$$r_0 = -\left[\frac{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} r_i q_i - \sum_{i=1}^{N} r_i^2 \sum_{i=1}^{N} q_i}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i}\right] \tag{9}$$

$$q_i = 10^{-0.05L_{pi}} \tag{10}$$

L_{pi} and r_i are, respectively, the SPL and the distance measured from the center to each position, and N is the number of measurement positions for each line over which the test is performed.

The deviations of the SPLs are then calculated with respect to the inverse square law using the following equation:

$$\Delta L_{pi} = L_{pi} - L_p(r_i)\ [dB] \tag{11}$$

where,

ΔL_{pi} is the deviation from the inverse square law in decibels, L_{pi} is the SPL of the measurement at the i-th position in decibels, and $L_p(r_i)$is the SPL at a distance r_i, estimated by the inverse square law in decibels. The deviations permissible according to ISO 3745 are shown in Table 1.

In the evaluation of the anechoic chamber, pink noise was used as excitation signal to generate sound with equal energy over the bandwidth of interest. The acoustic measurement equipment consists of a ¼-in 40BF free-field microphone (G.R.A.S, Denmark) as a receiving element for the acoustic signal and a conditioning amplifier, model 2690-0F2 (Bruel & Kjaer, Denmark), which prepares the signal before sending it to the data acquisition system. The sound source is an 8M300 coaxial speaker (8 ohm – 200 watts, Bellsound, ITALY) connected to a XA-950 amplifier (AIWA, Korea). For data acquisition, a U2531A system (Agilent, USA) connected to a computer was employed. The configuration of the experimental set-up is shown in Figure 6.

Table 1. Maximum permissible deviation of the sound pressure levels measured from the theoretical levels using the inverse square law. (ISO, 2003).

Type of test chamber	One-third-octave band frequencies [Hz]	Permissible deviation [dB]
Anechoic chamber	≤630	±1.5
	from 800 to 5000	±1.0
	from 800 to 5000	±1.5

Source: Adapted from [13].

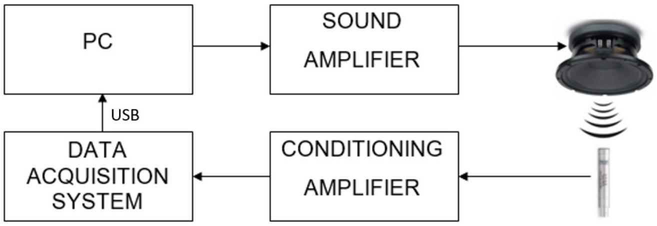

Figure 6. Diagram of the configuration of the experimental set-up. Source: The authors.

IV. RESULTS

The dimensions of the constructed anechoic chamber were selected to maximize the use of space available in our laboratory. As the principal dimensions of the enclosure were all different, no overlapping of the axial eigenfrequencies occurs. The eigenfrequency distribution of the designed chamber was computed and then the difference between adjacent frequencies was calculated. The mean intermodal frequency distance is 20 Hz. As there is no a general rule available regarding the minimum allowed frequency separation between adjacent eingenfrequencies, Figure 7 shows the distribution of the eigenfrequency separation of the chamber designed.

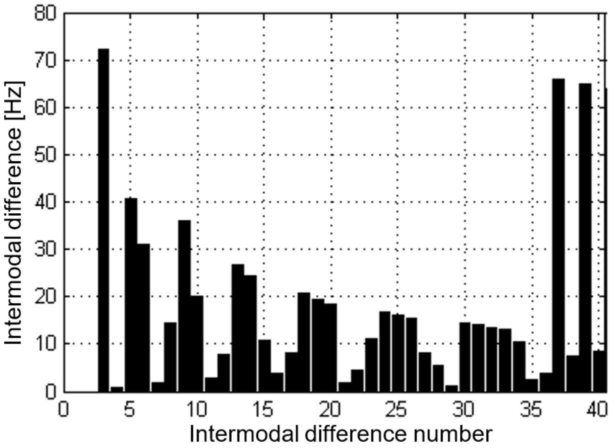

Figure 7. Result of the eigenfrequency separations obtained from the selected dimensions of the designed anechoic chamber. Source: The authors.

The results of the characterization of the anechoic wedges obtained by simulation are now presented. The experimental results of the material characterization and the assessment of the constructed chamber are also shown.

The material selected for manufacturing the lining was flexible open-cell D40 polyurethane foam, which has the highest sound absorption in the frequency range used for evaluation, i.e. a coefficient absorption above 0.9 at all frequencies of interest. Figure 8 shows the characterization results of the polyurethane roam samples in theKundt's tube. The lining of the chamber constructed consists of 3700 linear wedges of D40.

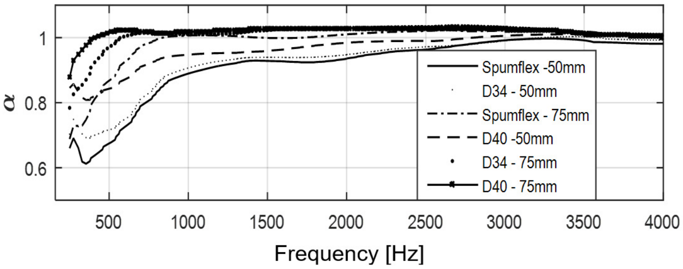

Figure 8. Sound absorption coefficients for D34, D40 and Spumflex foam. Two different thickness were used, i.e. 50 mm and 75 mm. Source: The authors.

In Figure 9, the results from the finite element model show that both the geometrical configuration of the designed wedges and the selected material provide very high absorption, i.e. the reflected sound pressure, at 20 cm from the wedges, is reduced in approximately 47 dB with respect to the incident plane wave.

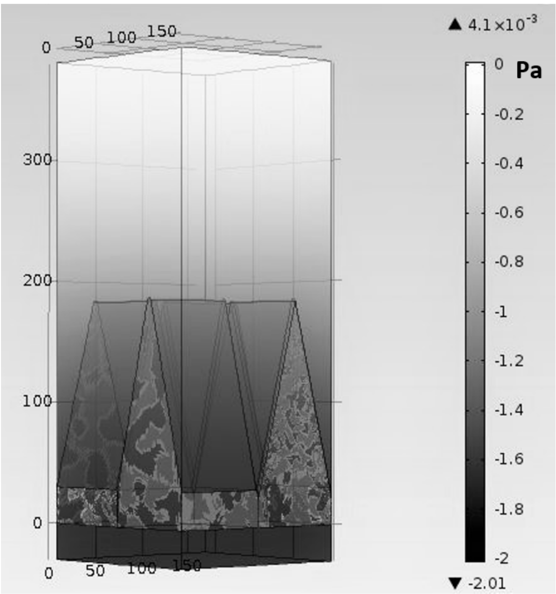

Figure 9. Estimated acoustic pressure (in Pascals) reflected by a set of four anechoic wedges at the cutoff frequency (400 Hz). Source: The authors.

A better performance is expected at higher frequencies. The properties of the material of the anechoic wedges were extracted from technical reports available for a polyurethane sample of D40 material: a porosity of 0.995, a flow resistivity of 10.5e3 $Pa \cdot s/m^2$, a tortuosity of 2, a viscous characteristic length of 240 µm and a thermal characteristic length of 470 µm. In spite of the theoretical character of this result, it allowed us to carry out relative comparison of the absorption performance of different configurations. This also enabled us to determine the optimal air gap between the chipboard and the base of wedges.

Strictly speaking, the acoustic evaluation showed that the chamber built, based on the designed cutoff frequency (400 Hz), is in conformance with the maximum values of deviation from the inverse square law stipulated in ISO 3745 (black dotted line in Figure 10) for frequencies higher than 500 Hz and up to 4 kHz. It is appreciated that one measured point is exceeding the limits by 1.0 dB at 500 Hz. Even though this might be attributable to possible reflections from near reflectors of the experimental setup, this result is also likely due to several causes, i.e. a small frequency distance between adjacent modes or, in the worst case scenario, a non-detected construction issue. Furthermore, it is important to mention that the chamber satisfies the limits that the standard establishes for a hemi-anechoic chamber. Also, as expected, the results showed that at frequencies below the nominal cutoff frequency, sound-pressure deviations exceed the limit stipulated.

The main conclusion from acoustic measurements is that the chamber is in conformance with the requirements of the standard in the direction and frequency range in which the test was performed. Similarly, it can be shown that the chamber meets the standard in different directions. This process is a viable alternative when undertaking a proper qualification without omnidirective sources, which are rather expensive. Similarly, it is possible to repeat the procedure for each desired direction; therefore, the characterization of sound sources can be performed over any path of interest.

The results of the evaluation of the background noise relative to the measured acoustic signal, presented in Figure 11, show that the acoustic signal corresponding to pink noise is more than 10 dB above the background noise in all frequency bands evaluated as suggested by the standard.

Although reverberation time is not a parameter included within ISO 3745, we estimate it for comparison with data reported in literature. Reverberation time allows to know how quickly the energy dissipates in a room, it can also be used as an indicator of the anechoic chamber's performance. Using equation (6) we estimate that the camera has a reverberation time of RT = 0.013 s, comparable with that reported by Luque and Quintanana in [1], RT = 0.0297 s. It should be noted that as the value is closer to zero the reverberation in the room is low, which is required to properly emulate the square inverse law.

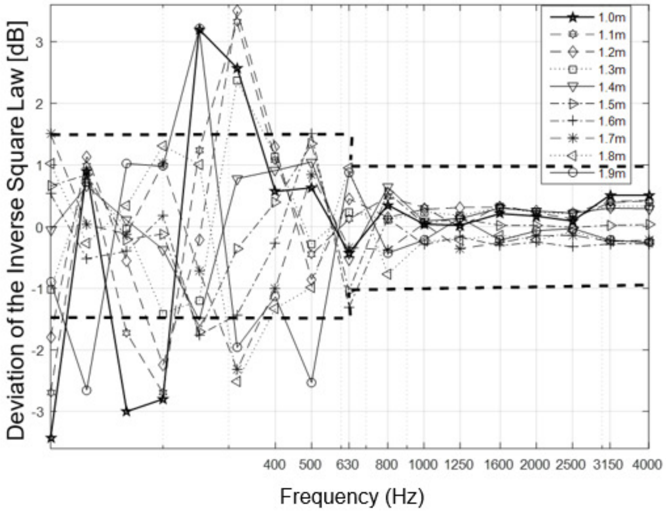

Figure 10. Results of the experimental evaluation of the inverse square law inside the anechoic chamber constructed, following the qualifying

methodology proposed by Gomez et al *[21]*. Results for one-third-octave band pink noise. Source: The authors.

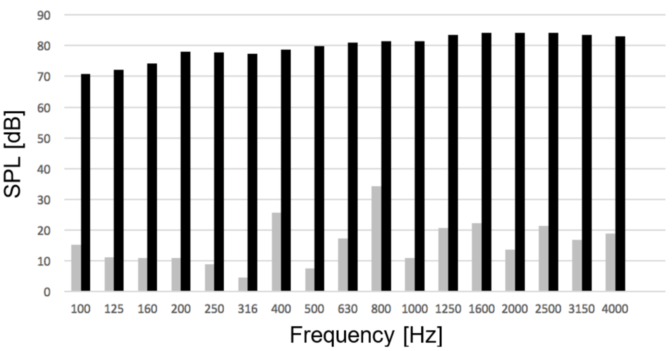

Figure 11. Results of the evaluation of the background noise of the anechoic chamber compared with the measured acoustic signal (pink noise). Source: The authors.

V. CONCLUSIONS AND DISCUSSION

It is possible to build a low-cost and easily installed anechoic chamber, using affordable materials available on the local market of sufficient quality, that complies with the requirements stipulated in ISO 3745. The total cost of the manufacturing materials used in the chamber prototype was $12,300.000 COP, corresponding to approximately 200 USD per square meter of effective built volume. The additional costs associated with manufacturing are estimated to be low because no specialized knowledge is required. If a lower cutoff frequency is intended, e.g 100 Hz, the cost per square meter would increase in approximately four times.

The proposed evaluation method involved the calculation of the level of deviation from the inverse square law along one of the diagonals of the constructed anechoic chamber. The results were satisfactory based on the designed cutoff frequency (400 Hz). While testing was not performed according to the standard, the results can be used to predict that similar results will be obtained along any other diagonal, under the assumption that the construction was uniform with respect to the distribution and attachment of the wedges to the structure.

Results showed that the anechoic chamber presented the best performance for frequencies between 500 Hz and 4 kHz for all points measured. Therefore, the constructed chamber can be used in the characterization of sound sources at frequencies exceeding that lower frequency limit. Although the process of complete testing is pending, the chamber in its current state is a useful tool for optimizing acoustic design or for analyzing the performance of a given sound source through relative comparison of experiments carried out in its interior. That is, repeating the screening test in the different directions of interest would be enough. Even though, in some cases, the requirements of the standard might not be met in all directions or frequencies, characterization results could still be useful to compare the performance of different samples of the same type of product.

The measured background noise satisfied the ISO recommendation, i.e., that there should be at least a 10dB difference between the background noise and the signal to be measured at all frequencies of interest.

Finally, the selection process of the construction materials, particularly the one needed to fabricate the wedges, showed that, in general, local manufacturers of foams are not aware of the commercial potential of their products for acoustic conditioning of enclosures. This study enables small- and medium-sized companies, by making a small investment, to add value to their products through characterization and subsequent mitigation or amplification, as appropriate, of the sound or noise their products emit. This study also contributes to the development and appropriation of knowledge in acoustics, which is a branch of physics of emerging importance in developing countries.

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