SURFACE ABSORPTION COEFFICIENT MEASUREMENT

DE BORTOLI, LUCIANO - LAIÑO, EMILIANO - STALDECKER, AGUSTIN

Universidad Nacional de Tres de Febrero, Acoustics Measurements and Instruments, Buenos Aires, Argentina
luciano.nicolas.de.bortoli@gmail.com
Universidad Nacional de Tres de Febrero, Acoustics Measurements and Instruments, Buenos Aires, Argentina
emilianolaino75@hotmail.com
Universidad Nacional de Tres de Febrero, Acoustics Measurements and Instruments, Buenos Aires, Argentina
agustaldecker@hotmail.com

Abstract - *This paper aims to study the behaviour of a Helmholtz resonator as a sound absorber, in this case, made of high density polystyrene (EPS), PVC tubes and cotton. Three different tube configurations are compared. As a second practice, three diverse array separations of the same configuration are analyzed. Finally, several sample surfaces with varying boundaries are tested. Results show that the designed resonator absorption performance behaves according to the phorus resonant frequency equation. Findings show an increase in absorption coefficient for increases in quantity of tubes used as well as surface coverage. Lastly, a correlation was achieved contrasting material and sample characteristics between sample size and absorption bandwidth.*

1. INTRODUCTION

Nowadays there are various materials and tools implemented to achieve an optimal acoustic design of an enclosure. This is done mainly by manipulating three basic aspects of sound: absorption, reflection and diffusion. Regarding the energy absorption of an acoustic hall for instance, the main influence can be attributed to the audience area, seats, constructive materials and even the air absorption. Often, special absorbers are intentionally placed as acoustic treatment depending on the requirements. Among these, the so-called acoustic resonators can be found, which are selective absorbent elements, widely used in acoustic conditioning with special use in low frequencies.

The aim of this paper is to design and build a working Helmholtz resonator that complies the theoretical equations which describes its behaviour. Various absorption coefficient measurements are carried out, including its relationship with the increase in tube quantity per resonator; the increase in surface area separation between samples; and finally, the increase in quantity of resonator samples.

Throughout this article, the calculations used to design a Helmholtz resonator are described and subsequently the standards followed for its measurements. Afterwards, results are exposed and discussed.

2. THEORETICAL FRAMEWORK

2.1 Porous Absorbers

There are two different kinds of absorbers, porous and resonators. Porous absorbers produce sound energy losses due to viscous boundary layer effects [1]. As the air enters the material through its interconnected pores, sound energy is dissipated via friction with the pore walls. This mechanism is only effective if there are plenty of air paths through the surface, so an open pore structure and a high porosity percentage is needed. Thermal conduction will also contribute to produce sound energy losses.

In order to create significant absorption, the porous absorber has to be placed where the particle velocity is high. If a sound wave travels incidentally to a wall, in its boundary the sound pressure will be the highest but the particle velocity will be zero. At a distance of $\frac{\lambda}{4}$ this velocity will be at its maximum. If low frequency absorption is intended, this distance will be very large, making porous absorption for low frequency impractical.

The two main properties that characterises porous absorption are resistance to airflow and porosity. The first one measures how easily air can enter to the absorber, and quantifies how much sound energy may be lost due to boundary layer effects. The porosity is a ratio of the total pore volume to the total volume of the absorbent. A good porosity ratio is often a symptom of good porous absorption. However, it is possible to trade off porosity against flow resistivity.

2.2 Resonant Absorbers

There are mainly two types of resonant absorbers: membrane absorber and Helmholtz absorber. The two of them follow the same principle: a mass vibrating against a spring. In a membrane absorber the mass is a sheet of material such as a wood panel which vibrates against an air enclosure or cavity (spring). By changing the vibrating mass and the stiffness of the air spring the resonant frequency can be shifted. In order to obtain sound absorption, a porous absorber is placed right behind the membrane, where particle velocity is higher.

2.3 Helmholtz' Resonator

In the Helmholtz absorber, the mass is the air travelling through a neck which vibrates against an air cavity.

It is most important to state that the airflow must behave as an acoustic mass while passing through the neck (moving without compressing), and as a compliance while in the cavity (compressing without moving). In order for this to happen, sound wavelength must be much larger than the resonator dimensions. Porous absorber must be set in the aperture of the neck, where high velocity air losses its energy more effectively.

To find the theoretical resonance frequency of a Helmholtz resonator, equation (1) is used. [1]

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{LV}} \tag{1}$$

Where c is the sound celerity; A, the tube section surface; L, the tube length; and V, the air cavity volume, as seen in Figure 1.

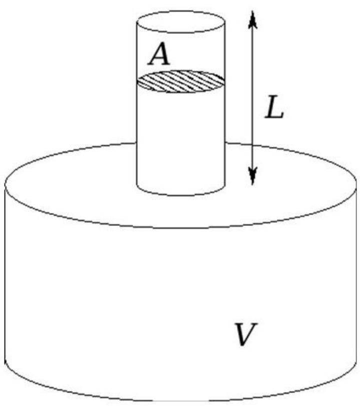

Figure 1. Helmholtz' resonator theoretical model

2.4 Resonator Panel

For the construction of practical resonators, shapes other than bottles can be used. Often, designs simply consist of perforated rectangular boxes. Each hole will have a radius and a depth dimension (t) which will become the theoretical tube length. Perforations are usually designed as an array, with a distance of separation (D).

The box will have a depth (d), which is the distance between inner faces of the resonator (frontal and rear). Resonators such as this make use of absorptive material attached to the inner face of the frontal panel, with a thickness (ta) as shown in Figure 2.

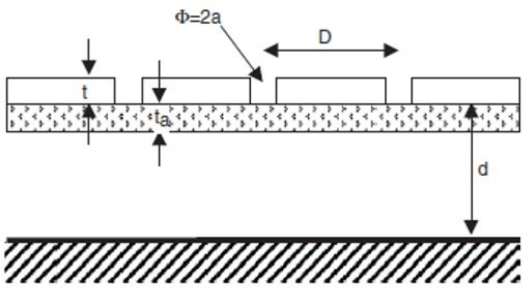

Figure 2. Helmholtz' resonator panel model

In this configuration, each tube will "see" a different effective volume, given by equation (2), illustrated in Figure 3.

$$V = D^2 d \tag{2}$$

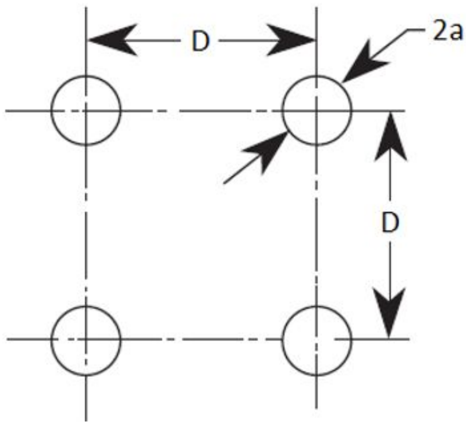

Figure 3. Resonator panel array model

The tube section remains as the multiplication between pi and each radius squared, however this is not the case for the tube's length.

The tube's effective length can be calculated knowing the tube's length (t) and radius (a), following equation (3).

$$t' = t + \frac{8a}{3\pi} \tag{3}$$

Finally, the resonance frequency is calculated using the parameters above in equation (4); this equation considers a porous panel material.

$$f = \frac{c}{2\pi}\sqrt{\frac{\varepsilon}{t'\,d}} \tag{4}$$

Where “ ε ” is the panel porosity, given by equation (5),

$$\varepsilon = \frac{n\,\pi\,a^2}{D^2} \tag{5}$$

2.5 Reverberation Time

Reverberation Time (RT) is a measure of the rate of decay of sound. It is defined as the time in seconds required for the sound intensity to drop 60 dB from its initial level [2].

In practice, it is difficult to measure a 60 dB decay because of the noise floor, which often prevents the signal from decaying within a dynamic range lower than 60 dB. Therefore, a common practice is to evaluate the time taken for the reflections to decay by 20 dB or 30 dB instead. These readings can then be extrapolated to a decay time of 60 dB. Thus, the reverberation time T20 is calculated as 3 times the time to decay by 20 dB and T30 is calculated as 2 times the time to decay by 30 dB.

2.5.1 Sabine’s equation

Sabine’s reverberation equation (6) was developed in an empirical way. Making measurements in two lecture halls, he observed that reverberation time depends on room volume and absorption area.

$$RT = \frac{0{,}161\ V}{\sum_{i=1}^{n} Si\ \alpha i} \tag{6}$$

Where V is the room volume; Si, the material surface area; and αi, the respective absorption coefficient. The denominator of Sabine’s equation is the acoustic absorption area, in m^2.

2.5.2 Eyring-Norris’ equation

Because Sabine proposed this equation assuming the sound field is diffuse, there are cases in which it is not accurate, especially when there is a high absorption. For this case the Eyring’s equation was developed. The Eyring-Norris’ equation (7) is designed in order to be used where the average absorption coefficient is more than 0,25.

$$RT = \frac{0.161\ V}{-S\ ln\,(1-\widehat{\alpha})} \tag{7}$$

Where V is the room volume; S, the total surface of the room, and $\widehat{\alpha}$, the average absorption coefficient.

The problem of using this equation is that the average absorption coefficient applies parameters calculated with Sabine’s formula, thus, making the method inaccurate again.

2.4 Edge Effect

When trying to measure the acoustic absorption coefficient of a material, a common systematic source of error is the edge effect. If an absorbing sample presents uncovered edges, it will usually absorb more sound energy relative to its bidimensional surface area [3]. This is the reason why absorption coefficients higher than 1 can be found. This is due to diffraction along the absorptive edges, which maximizes the overall absorption of the sample.

When performing a measurement, this edge effect can be reduced (although not completely eliminated) by covering the free edges of the sample with a reflecting frame.

3. PREVIOUS STUDIES

The Helmholtz absorber has been a subject of study among the years, and many papers have been written about its design and measurement.

In 1953 Ingard [4] studied the effect of different aperture geometries on the resonance frequency. He concluded that for values of porosity below 20% the geometry of the aperture has no incidence, but for higher values it has to be calculated separately with the formulas given. The interaction between two circular apertures is also studied, showing that the closer the holes are set, the higher the mass reactance is. So, in order to obtain maximum acoustic reactance, the open area should be concentrated in one single aperture in the center of the tube.

Vercammen [5] (2010) carried out the measurement of four samples of mineral wool in 15 different reverberation chambers along Europe, in order to prove the lack of accuracy of the ISO 354 standard. The results showed a poor reproducibility, being caused by the lack of a diffuse field in the chambers. Also its geometry and the presence of diffusers have a strong influence, but the standard does not account for it. Vercammen also states that it is common that the absorption coefficient gives values higher than one. This is related to the use of Sabine's formula instead of Eyring's one, and to the fact that the edge effect is not considered in most of the measurements.

In 2014 Valtonen [6] designed the acoustic treatment of a shopping mall in Finland, which had a poor intelligibility because of a high reverberation time in mid frequencies. The design consisted in a perforated panel which was modeled in 3D with a computer simulator, showing the effect of the different parameters. A comparison between the proportion of mineral wool and air cavity was carried out, proving that the most absorptive one was with the air cavity 100% full of mineral wool.

Selamet and Lee [7] investigated in 2003 theoretically, numerically and experimentally the performance of the resonator neck with different shapes and lengths. They concluded that the extension of the neck into the cavity lowers the resonance frequency and narrows the Q. Also the shape of this extension and the perforation can change this frequency. This is important because the resonant frequency can be shifted without changing the cavity volumen.

In 2016 an investigation was conducted as part of the refurbishment of the Queen Elizabeth Hall in London [8]. They studied the performance of the 2300 Helmholtz resonators of the Hall by constructing a bank of replicas and measuring them. They proved that by lowering the open area the resonant frequency lowers too. Polyurethane Foam was added as porous absorber, broadening the frequency response and making the resonator more efficient. Also the effect of adding curtains was studied, increasing the absorption at all frequencies, especially at the lower bands.

Daniel [9] stated in 1960 that the sound absorption coefficient for a small area of an acoustical material is much greater than for a very large one. This is because the diffraction phenomenon involved, making the absorbent surface near the edge to absorb more sound power than an equal area near the center. An equation to calculate this is given, proportional to the admittance of the material and to the wavelength, and inversely proportional to the border length.

4. RESONATOR DESIGN

In this section is shown the design of the helmholtz resonator used for measurements in different configurations.

4.1 Chosen parameters

Given the available materials, 1 m^2 polystyrene panels (EPS) are intended to be used for the box construction. To close the box, a couple of panels are subdivided to make 10 subpanels with dimensions: 1 m x 0.96 m (considering panel depth of 2 cm). This derived panels are intended to be used as walls for each box. Therefore, the resonator depth (d) is fixed to 10 cm.

For simplicity, it was decided that a maximum of five PVC tubes per resonator would be installed, each with a total length (t) of 5 cm, necessary lower than the distance d as the tubes are attached from the inside of the box. From the available tube diameters, a 25 mm radius (46 mm inner diameter) tube was chosen as it was considered to be large enough to allow the passage of air without reducing its speed considerably.

Finally, the array separation distance for the five tubes was designed in such a way that when all tubes are put together and individual resonators are combined in one large sample, they form a homogenous distribution of holes, for every instance of the measurement.

4.2 Resonance Frequency

From section 4.1, parameters used in equation (4) can be derived. Parameters are shown in Table 1.

Table 1: Design Resonator Parameters

Parameter	Value
Depth (d)	0.1 m
Tube thickness (t)	0.05 m
Effective tube thickness (t')	0.07 m
Tube radius (a)	0.024 m
Tube separation distance (D)	0.25 m
Porosity Coefficient (ε)	0.144

Therefore, theoretical resonance frequency is calculated and shown in equation (8).

$$f = 248.60\ Hz \tag{9}$$

4.3 Final Model

The final resonator model described in previous sections is shown in Figures 4-

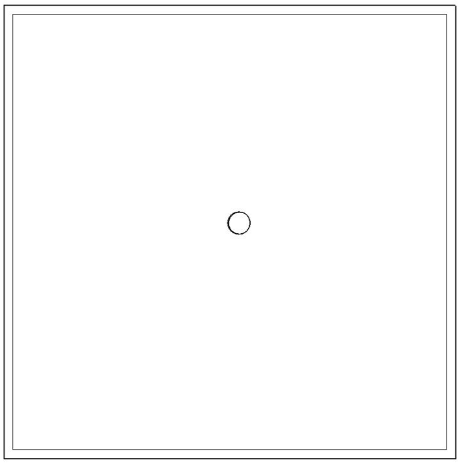

Figure 4: Resonator design, 1 tube, used for both linear and diagonal arrangements.

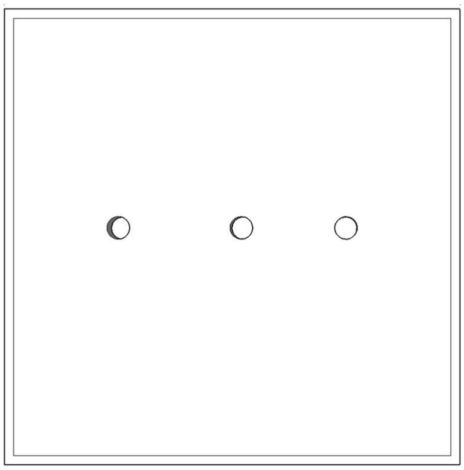

Figure 5: Resonator design, 3 tubes, linear arrangement.

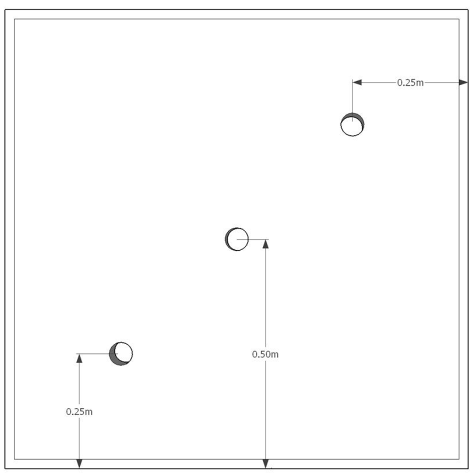

Figure 6: Resonator design, 3 tube, diagonal arrangement.

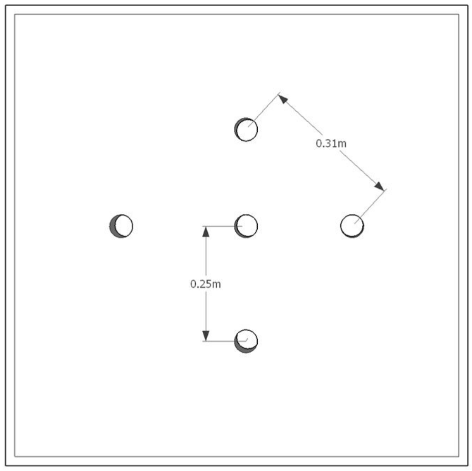

Figure 7: Resonator design, 5 tubes, linear arrangement.

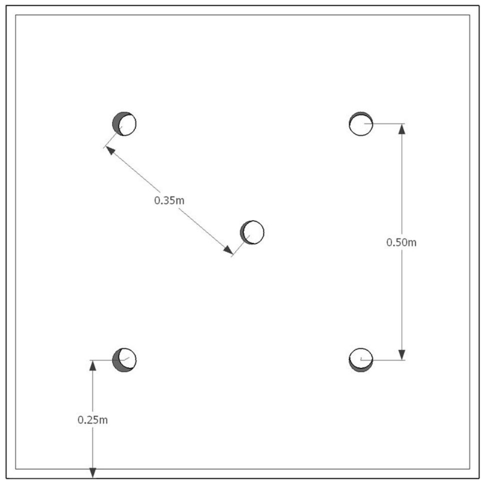

Figure 8: Resonator design, 5 tubes, diagonal arrangement.

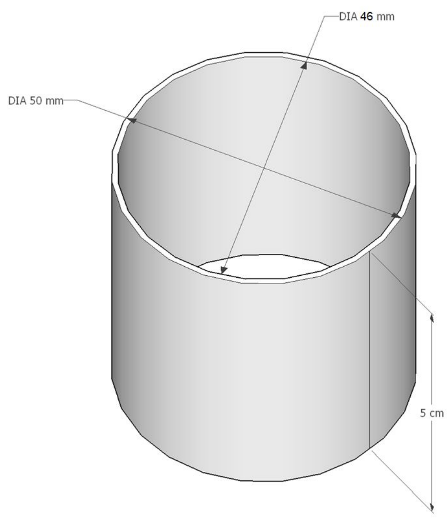

Figure 9: Tube dimensions

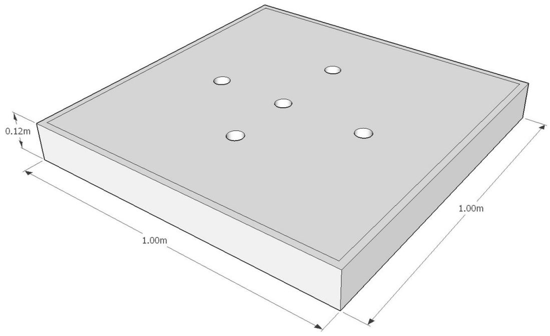

Figure 10: 3D Resonator design, 5 tubes, linear arrangement.

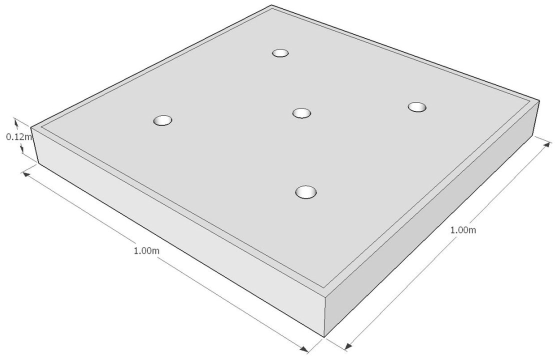

Figure 11: 3D Resonator design, 5 tubes, diagonal arrangement.

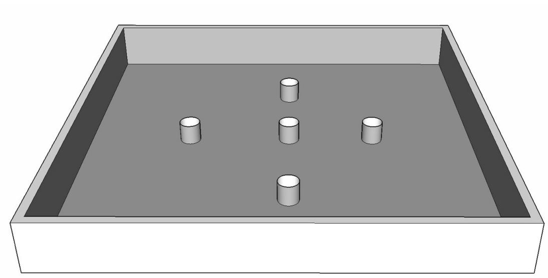

Figure 12: 3D Resonator design, 5 tubes, Linear arrangement, inner view.

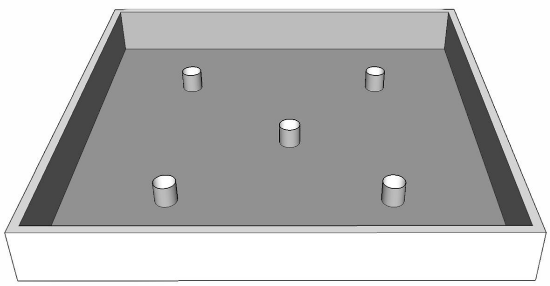

Figure 13: 3D Resonator design, 5 tubes, Diagonal arrangement, inner view.

5. METHOD

5.1 Standard

5.1.1 ISO 354 Requirements

The standard used in this measurement is ISO 354:2003, which describes the method to measure the absorption coefficient of a material in reverberant chambers. Basically, the reverberation time in the chamber is measured with and without the sample to be studied, and from these values the Sabine absorption area for each condition is determined. Then, from a subtraction between these results, the area of absorption of the sample is obtained, which allows to calculate its absorption coefficient as well. In first place, there are some conditions that the enclosure must meet, which are detailed in Table 2.

Table 2: ISO 354 Main Requirements

Specification	Condition
Room Volume	$V > 150\ m^3$
Maximum Diagonal	$D_{max} < 1{,}9V^{1/3}$
Sample Surface	$10\ m^2 < S < 12\ m^2$

In addition, the enclosure must be sufficiently diffuse to guarantee an uniform average energy at any point inside the room. The equivalent sound absorption area of the empty chamber must not exceed the values shown in Table 3. If the volume of the enclosure differs from 200 m^3, the listed values must be multiplied by $(V/200)^{2/3}$.

Table 3: Maximum equivalent absorption area

Frequency [Hz]	absorption area [m^2]
100 - 800	6.5
1000	7
1250	7.5
1600	8
2000	9.5
2500	10.5
3150	12
4000	13
5000	14

The curve of the equivalent sound absorption area of the chamber as a function of frequency should show a smooth function with no peaks that differ more than 15% from the average of the two-thirds octave contiguous values.

For flat absorbers, the sample must have an area between 10 and 12 m^2. The sample must have a rectangular shape with a wide-long ratio between 0.7 and 1. It must be placed in such a way that no part is less than 1 m from the edges of the camera, or at least 0.75 m. Also, preferably the edges of the sample should not be placed parallel to the nearest edge of the chamber.

Measurements should be made with different microphone positions that are at least 1.5 m apart, 2 m from any sound source and 1 m from any surface of the camera and the sample. Also, the source positions must be at least 3 m apart.

The minimum number of microphone positions must be three and the minimum number of sound source positions must be two. For each instance there must be a minimum of twelve impulse response measurements.

5.1.2 Absorption Coefficient Calculation

The calculation of the absorption coefficient is done by measuring the reverberation time in the reverberant chamber with and without the sample.

The reverberation time of an enclosure is related to its total absorption area, as expressed in Sabine's equation. Therefore, the absorption area of the empty room is obtained following equation (10).

$$A_1 = \frac{55{,}3V}{cT_1} - 4Vm_1 \qquad (10)$$

Where V is the volume of the enclosure; c, the speed of sound; T_1 the reverberation time of the empty room; and m_1 the sound attenuation coefficient calculated according standard ISO 9613-1 [10].

It is important to state that the Standard requires that the reverberation time calculated is the RT20, evaluating the fall from -5 dB to -25 dB, and then multiplying this value by 3.

Once obtaining the absorption area of the empty room, the sample is positioned inside the enclosure and the process is repeated to obtain the total area absorption of the room with the sample, as shown in equation (11).

$$A_2 = \frac{55{,}3V}{cT_2} - 4Vm_2 \qquad (11)$$

To obtain the area of absorption of the sample, a difference is made between the two values mentioned, as shown in equation (12).

$$A_T = A_2 - A_1 \qquad (12)$$

Finally, the absorption coefficient of the sample is obtained by dividing the previous expression by its surface, as shown in equation (13).

$$\alpha_S = \frac{A_T}{S} \qquad (13)$$

The relative standard deviation of the reverberation time evaluated in a decrease range of 20 dB given by ISO 354 Standard is shown in equation (14).

$$\varepsilon_{20}(T)/T = \sqrt{\frac{2{,}42+3{,}59/N}{fT}} \qquad (14)$$

Being ε_{20} the standard deviation of T_{20}, T the reverberation time measured, f the central frequency of the third of octave band and N the number of impulse responses evaluated.

The standard deviation is considered the typical uncertainty for the complete measurement. By using a k factor of 2, the expanded uncertainty can be calculated for a confidence value larger than 95%.

5.2 Reverberant Chamber

Previous to the selection of the measurement chamber, various options were analysed considering room volume, maximum diagonal limitations and maximum absorption area following ISO 354 recommendations. While the possibility of complying with the maximum diagonal was available, the room chosen exceeded this length by a metre, however it satisfied the minimum room volume, which was considered more relevant. Before the measurement, an estimative calculation of the equivalent absorption area for every third octave band was done, choosing materials from Cox references that best fitted the ones in the candidate room, in order to evaluate if the chamber complied with the maximum requirements. This calculations are not shown in this paper, but within an annexed excel sheet. Results were favourable, as every band was below the maximum values.

The room chosen for the measurement as a reverberant chamber is a multipurpose room at the 11th floor of a building located in Ciudad Autónoma de Buenos Aires, Argentina. This is a highly reverberant chamber with strong reflective surfaces, so it can be used as a Reverberation

Chamber. The main source of noise inside the room comes from the street outside the building, but as measurements were performed at night this was very low. In the Results and Discussion section there will be given values of Reverberation Time and Background Noise.

In order to fulfill the standard, a minimum volume of 150 m3 is needed. As can be seen in Table 4, the volume of the chamber is 152,86 m3 so this minimum requirement is accepted. Values of the total surface and the diagonal are also given. As the maximum diagonal for this chamber is 10,16 m, this requirement is not fulfilled.

Table 4: Chosen chamber specifications

Specification	**Value**
Room Volume	152,86 m3
Room Surface	192,34 m2
Max. Diagonal	10,16 m
Diagonal	11,99 m

In Figure 14 the Reverberant Chamber footprint is shown with its dimensions. Its height is 2.80 m; it has 6 walls with lengths that range from 1.20 m to 10 m. The floor has a small degree of inclination.

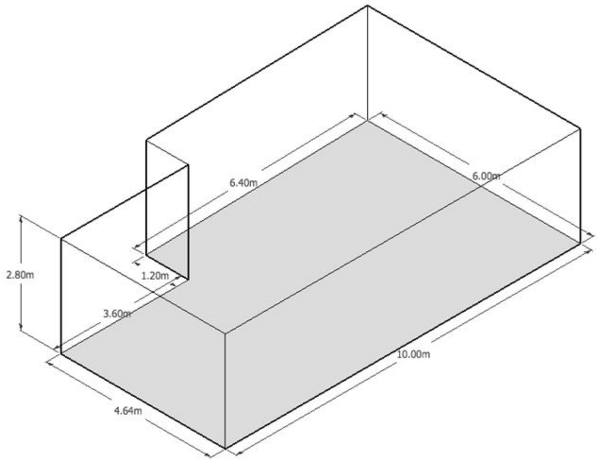

Figure 14. Reverberation Chamber 3D Model.

Figures 15 and 16 show actual pictures of the room, which is mainly composed by hard surfaces. The floor is formed by tiles, the walls by cement, and the largest surface is a 5 mm glass window which is highly reflective.

Figure 15. Front view of the Reverberant Chamber.

Figure 16. Rear view of the Reverberant Chamber.

5.3 Measurement

Measurements take place between November 4th and 6th of 2017 during a practice belonging to the subject “Acoustical Instruments and Measurements”, Universidad Nacional de Tres de Febrero.

5.3.1 Equipment

To carry out the measurements, the following equipment is used:

- Focusrite Scarlett 18i6 Audio Interface
- 2 Behringer EMC8000 Microphones
- Stands and XLR cables
- Banghó MAX G101 Notebook
- 41 Balloons

In order to proceed with the measurement, the two microphones are connected to the audio interface, which is connected via USB to the notebook, running Cubase 5 DAW. Phantom power (+48V) is used for both microphones. The gain is set to 6.5 for both channels as it corresponds to the calibration for 114 dB SPL, chosen considering the balloons as source.

The signal flow between all the measurement equipment is shown in Figure 17.

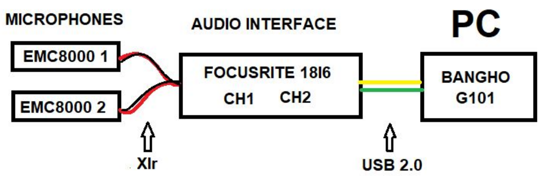

Figure 17. Equipment connection configuration.

5.3.2 Measurement Set-up

Following ISO 354 requirements, 12 different measurements for each arrangement are needed. To achieve this, 4 microphone positions and 3 source positions are settled respecting the requirements listed above. This positions can be seen in Figure 18.

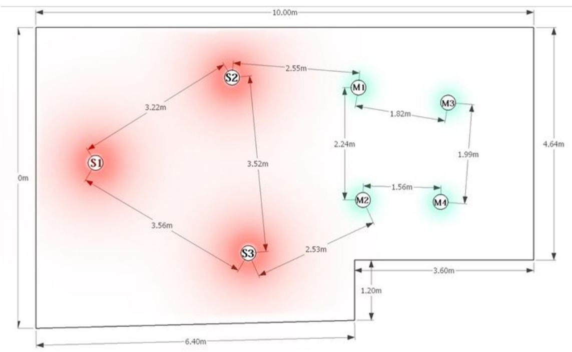

Figure 18. Microphone and source positions.

Since only two microphones are available, two balloons have to be bursted in order to complete the 4 microphone positions.

Observing the previous figure, it can be checked that all minimum distances required by the standard are complied.

5.4 Sample Arrangements

5.4.1 Practice I

For Practice I, three different arrangements of the resonator are used for the same surface. This surface is the sum of the plane area occupied by the 9 expanded polystyrene (EPS) samples and their boundary sides. The plane area gives a surface of 9 m^2 and the borders 1,44 m^2, so the total absorption surface used for the calculus is 10,44 m^2. It is important to sum the edges area of the samples as the EPS is absorptive at mid frequencies. If it is not considered, the absorption coefficient will be higher than it really is because of the edge effect explained before.

The first arrangement consists of only 1 aperture in each panel, leading to a total of 9 necks in the whole arrangement, with the cotton attached to the aperture of the neck. The second arrangement has 3 apertures in each panel, leading to a total of 27 holes in the whole arrangement. Finally, the third arrangement consists of 5 apertures in each panel, so 45 holes are in total. Arrangements for practice I are shown in Figures 19-24.

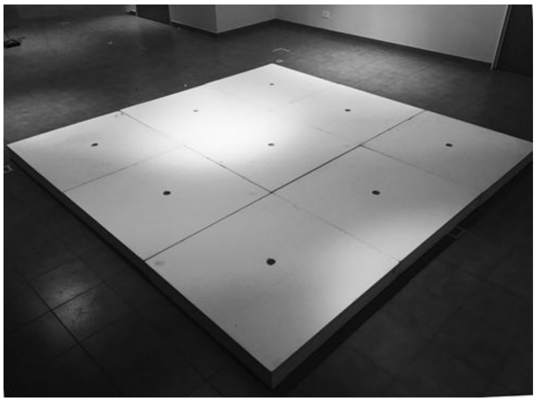

Figure 19. First Arrangement, Practice I

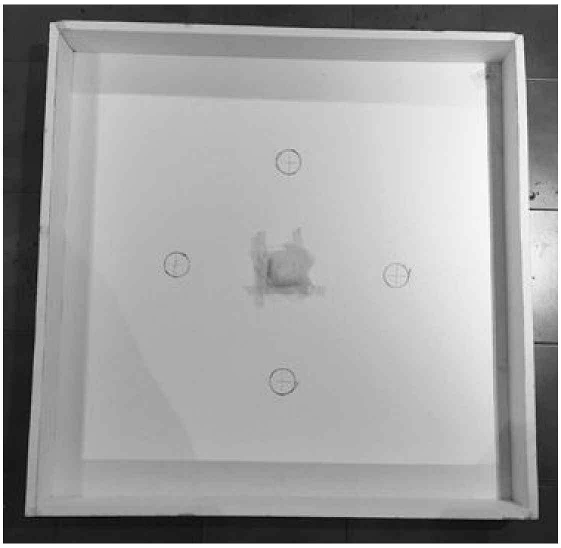

Figure 20. One tube per sample, inner view

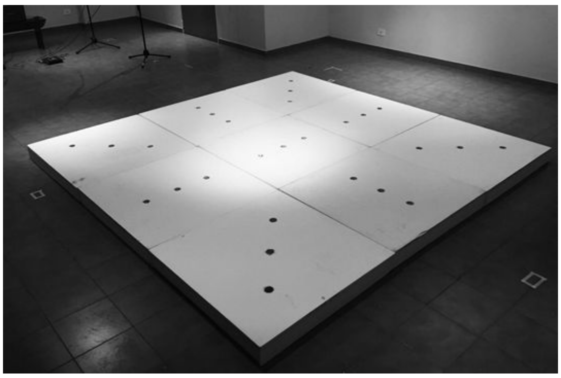

Figure 21. Second Arrangement, Practice I.

Figure 22.Three tubes per sample, inner view

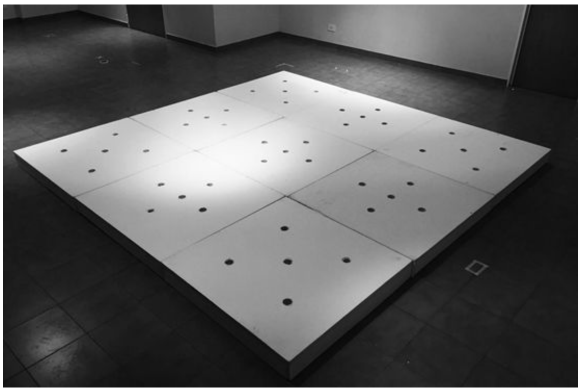

Figure 23. Third arrangement, Practice I.

Figure 24. Five tubes per sample, inner view.

5.4.2 Practice II

For Practice II, three different surfaces arrangements are settled for the same surface area (10,44 m2). The aperture's arrangement used is the third of the previous practice, meaning that in each panel there are 5 holes.

The first surface arrangement is also the same as the third one of the previous practice, with all the panels close together as can be seen in Figure 10.

The second surface arrangement consists in separating each panel 10 cm away. For this arrangement, the surface area used for the calculus is 13,32 m2. This comes from the sum of 9 m2 of the panels plus the borders area, which now are exposed in their totality and form an area of 4,32 m2.

The third arrangement has a separation of 40 cm between each panel, as can be seen in Figure 13. The surface area is the same that in the second one.

Arrangements for practice II are shown in Figures 25-26.

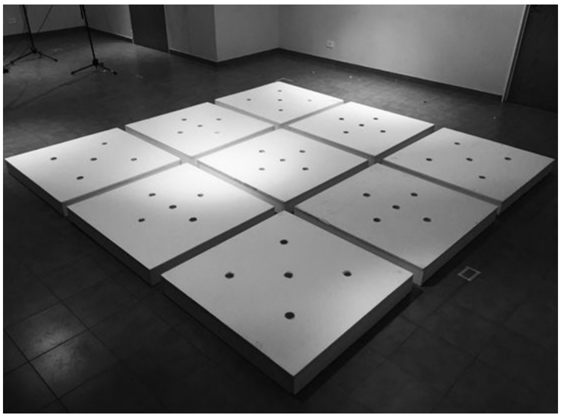

Figure 25. Second Arrangement, Practice II.

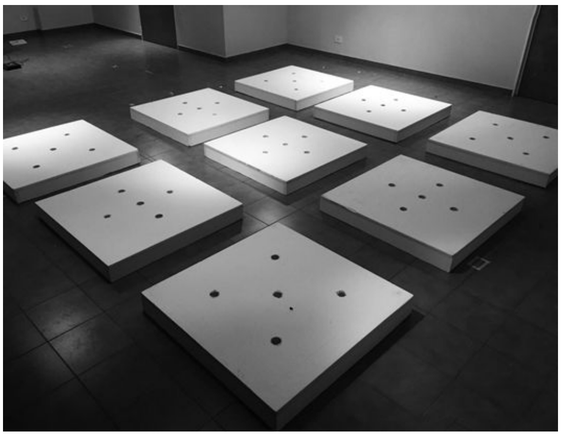

Figure 26. Third Arrangement, Practice II.

5.4.3 Practice III

For Practice III the aim is to observe how the absorption coefficient changes by the addition of samples. At first, only 1 sample is measured. Then another sample is added, measuring 2 of them, and progressively increasing its number up to 4, 6, 8 and 9 samples. This last one is the previously measured in Practice I and can be seen in Figure 23. The rest of the arrangement of Practice III are shown in Figures 27-31.

Figure 27. One Sample, Practice III.

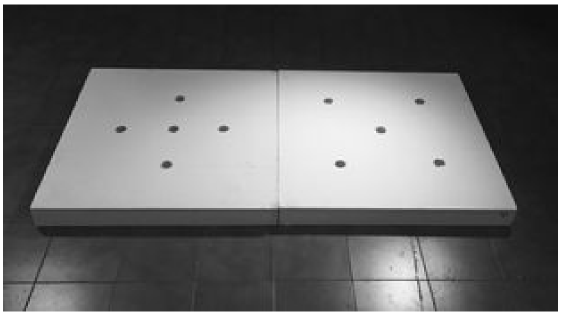

Figure 28. Two Samples, Practice III.

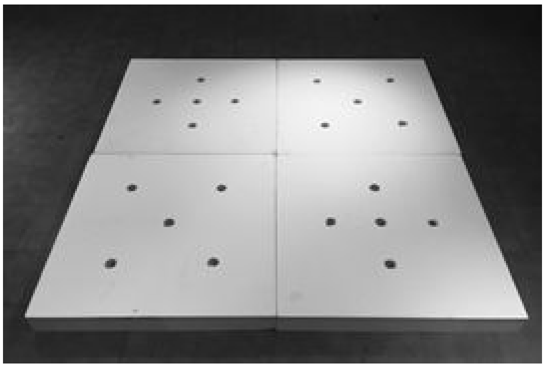

Figure 29: Four Samples, Practice III.

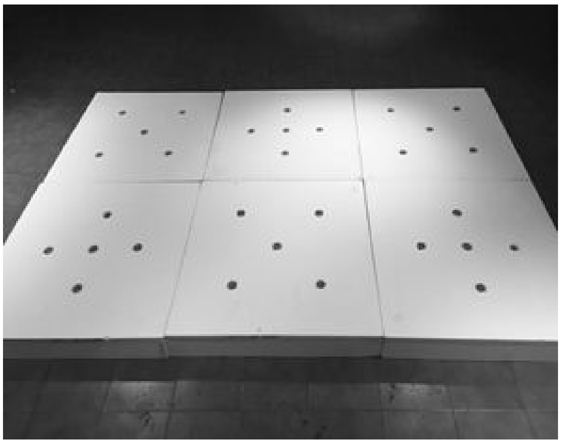

Figure 30. Six Samples, Practice III.

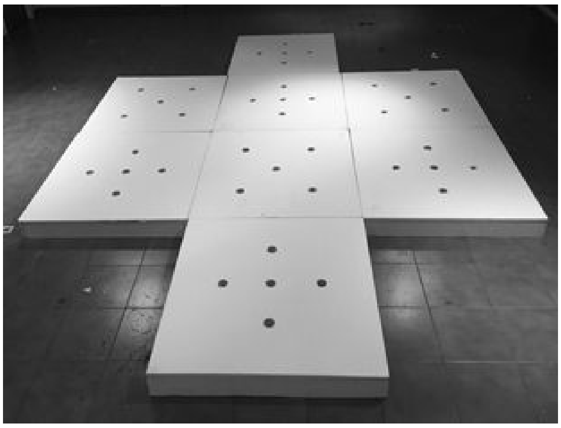

Figure 31. Eight Samples, Practice III.

The surface area used for the absorption coefficient calculation is different for each number of sample. Table 5 shows this value for each arrangement.

Table 5: Surface Area for each number of samples.

Number of Samples	Surface Area [m^2]
1	1,48
2	2,72
4	4,96
6	7,20
8	9,68
9	10,44

6. RESULTS & DISCUSSION

6.1 Reverberation Time

Firstly, the Reverberation time of the empty room is obtained using Aurora "Acoustical Parameters" Module in the Audacity environment. RT third octave results are shown in Figure 32.

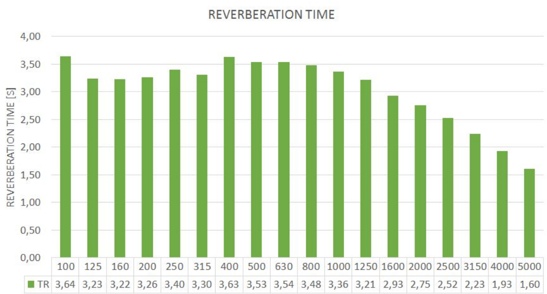

Figure 32. Reverberation Time (RT20) of the empty room.

This values show that from 100 Hz up to 1250 Hz the room is significantly reverberant, as the RT20 is over 3 s. From 1600 Hz up to 5000 Hz there is a decay mainly due to air absorption. Because Sabine formula shows an inverse relationship between RT and equivalent absorption area, large RT values are translated to low A values. The air absorption is independent of A and only considers the room volume, a large volume in this case. Therefore, air absorption has a greater impact on RT values in a large rooms for higher frequencies.

6.2 Background Noise

In order to check if the difference between signal and background noise is greater than 10 dB as required by the standard, a comparison between each third octave sound pressure level is made. For this comparison, from the total of 12 ballon explosions for the empty room measurement, the results with lower SPL in each third octave band are compiled, generating a curve with the absolute minimum signal levels.

This curve then is contrasted with the background noise, which in this case consist in the compilation of the maximum SPL values registered. A third curve is generated, given by the SPL difference between the minimum signal and maximum noise results. The purpose of this difference curve is to validate all measurements by testing the worst case scenario. The curves are shown in Figure 20. Calculation are done with the use of a sound meter GUIDE app developed in the Matlab environment, from a previous work.

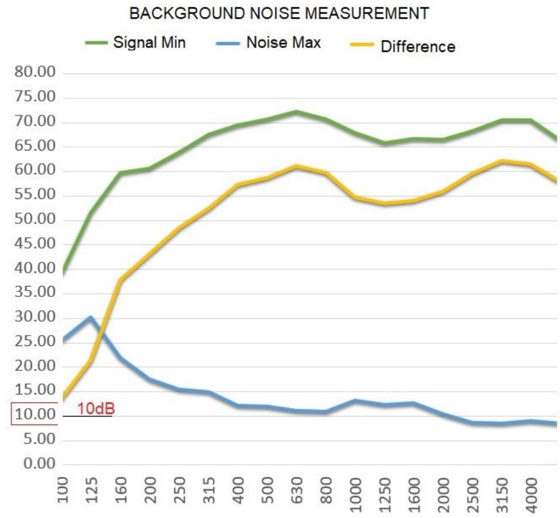

Figure 33. Comparison between the SPL of a balloon and the background noise.

It can be observed that the difference between the balloon's SPL and the background noise if higher than 10 dB for the frequencies of interest, therefore, the standard requirement is checked. It is noted that this difference is lower than 10 dB for frequencies under 100 Hz, however, this range is not considered by the standard.

6.3 Absorption

6.3.1 Practice I

The three arrangements with varying quantities of tubes (1, 3 and 5) are processed with an annexed excel sheet. Results of absorption coefficient for every third octave band of interest is shown in Figure 34 and Table 6.

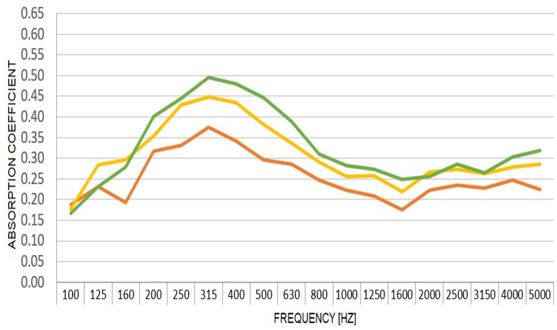

Figure 34. Absorption coefficient for arrangements of Practice I.

It can be observed that as the number of tubes increase, the absorption coefficient increases. From a peak value of 0,37 for the first arrangement it increases to 0,45 for the second one, reaching to its major peak of 0,50 for the third.

This peak value remains in the third octave band 315 Hz for the three arrangements. This means that the resonance frequency doesn't change with the number of tubes used per sample. This may be due to necks being separated at a prudence distance so they do not interfere with each other, meaning that the air volume inside the cavity is the same in every case. The fact that the absorption is augmented is justified by the increasing numbers of apertures, which results in increased airflow and added porous material. It is important to mention that the resonance frequency measured (in the band 315 Hz) does not appear to be exactly the same as the one calculated for the design (248,6 Hz). This might be caused by imperfections in the neck's cutting, which had irregularities in the borders. Cox and D'Antonio [1] states that this generates turbulence, which increases the acoustical mass and thus raises the resonant frequency.

Table 6: Practice I Absorption Coefficient

F [Hz]	I	II	III
100	0.19	0.18	0.17
125	0.23	0.28	0.23
160	0.19	0.30	0.28
200	0.32	0.35	0.40
250	0.33	0.43	0.44
315	0.37	0.45	0.50
400	0.34	0.43	0.48
500	0.30	0.38	0.45
630	0.29	0.34	0.39
800	0.25	0.29	0.31
1000	0.22	0.26	0.28
1250	0.21	0.26	0.27
1600	0.18	0.22	0.25
2000	0.22	0.27	0.26
2500	0.23	0.27	0.28
3150	0.23	0.26	0.26
4000	0.25	0.28	0.30
5000	0.22	0.28	0.32

6.3.2 Practice II

Measurements are conducted placing the 9 absorbers in three different surface separation arrangements (0 cm, 10 cm and 40 cm). Results are shown in Figure 35 and Table 7.

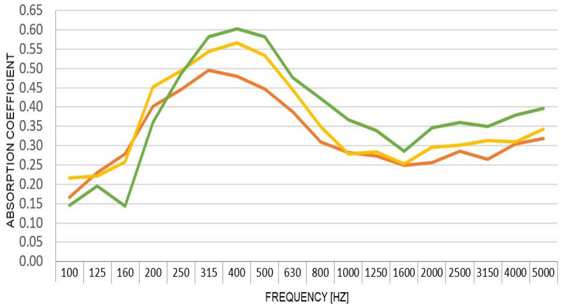

Figure 35. Absorption coefficient for arrangements of Practice II.

Table 7: Practice II Absorption Coefficient

F [Hz]	I	II	III
100	0.17	0.22	0.15
125	0.23	0.22	0.20
160	0.28	0.26	0.14
200	0.40	0.45	0.36
250	0.44	0.49	0.49
315	0.50	0.54	0.58
400	0.48	0.57	0.60
500	0.45	0.53	0.58
630	0.39	0.45	0.48
800	0.31	0.35	0.42
1000	0.28	0.28	0.37
1250	0.27	0.28	0.34
1600	0.25	0.25	0.29
2000	0.26	0.30	0.35
2500	0.28	0.30	0.36
3150	0.26	0.31	0.35
4000	0.30	0.31	0.38
5000	0.32	0.34	0.40

As can be seen in the Figure 35, the more separated the samples are, the higher the absorption coefficient is. From a maximum value of 0,5 for the first arrangement, it raises up to 0,57 for the second one, and finally a value of 0,6 is given for the third. The raise in the overall absorption coefficient is produced by the progressive augmentation of the edge effect. As the separation between samples increases, the diffraction over the edges is higher so there is more absorption at the sides.

There is also a raise in the resonant frequency, shifting from 315 Hz to 400 Hz. This may be because the borders are made of EPS which have its maximum absorption around 500 Hz.

6.3.3 Practice III

Finally, the number of resonator samples is increased (1, 2, 4, 6, 8 and 9) in order to find a correlation between sample surface area and absorption coefficient. Results are shown in Figure 36 and table 8.

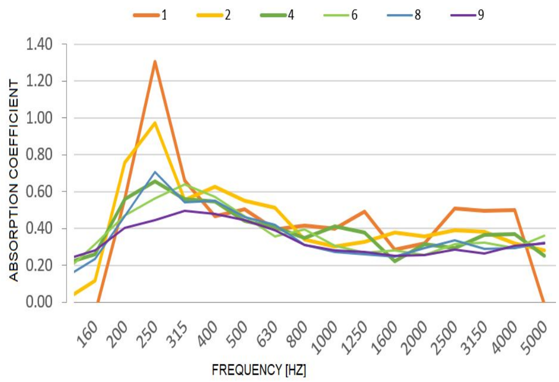

Figure 36. Absorption coefficient for arrangements of Practice III.

Results in Figure 23 show that for a lower number of samples the absorber is more selective. This is because a raise in the number of samples means an increment in the porous material at the apertures, which correlates to an increase in acoustic resistance, so the selectivity decreases, and the resonator works for a broader frequency range.

It is clear to see that the resonance frequency for one sample is centered in the 250 Hz third octave band, which is significatively close to the theoretical resonant frequency (248.60 Hz) calculated in the design section. As the number of samples grows, this frequency increases up to 315 Hz, mainly because of the imperfections in the apertures previously described.

It is shown that the absorption coefficient for one sample reaches values higher than 1. This is because the surface area is too small compared to the whole area of the reverberant chamber, so the edge effect is maximized. This is why the ISO 354 Standard requires sample surfaces between 10 m2 and 12 m2, in order to give appropriate values. Another source of error is the fact that for Practice III, only one balloon was used for each measurement, whereas 12 balloons were used for practice I and II. Consequently, results may be influenced by the modes of the room.

Table 8: Practice II Absorption Coefficient

F[Hz]	I	II	IV	VI	VIII	IX
100	1.26	0.81	0.42	0.40	0.22	0.17
125	-0.58	0.01	0.21	0.16	0.13	0.23
160	-0.06	0.12	0.26	0.31	0.23	0.28
200	0.56	0.76	0.56	0.47	0.47	0.40
250	1.31	0.97	0.65	0.56	0.70	0.44
315	0.66	0.55	0.56	0.64	0.54	0.50
400	0.47	0.63	0.55	0.57	0.55	0.48
500	0.51	0.55	0.44	0.47	0.46	0.45
630	0.39	0.51	0.41	0.36	0.42	0.39
800	0.41	0.34	0.35	0.39	0.31	0.31
1000	0.40	0.30	0.41	0.31	0.27	0.28
1250	0.49	0.33	0.38	0.27	0.26	0.27
1600	0.29	0.38	0.22	0.28	0.25	0.25
2000	0.32	0.36	0.32	0.26	0.29	0.26
2500	0.51	0.39	0.29	0.31	0.34	0.28
3150	0.49	0.38	0.37	0.32	0.29	0.26
4000	0.50	0.32	0.37	0.29	0.29	0.30
5000	-0.02	0.28	0.25	0.36	0.32	0.32

6.3.4 Designed Resonator Absorption

If the designed resonator was intended for commercial production, a material and sample absorption coefficient value should be provided. The material coefficient will be closer to Practice I Measurements, while the sample coefficient should be closer to Practice II or III Measurements, depending on the configuration. In Figure 37 it is shown the absorption coefficient smoothed curve for one sample, which represents one unit of the resonator designed.

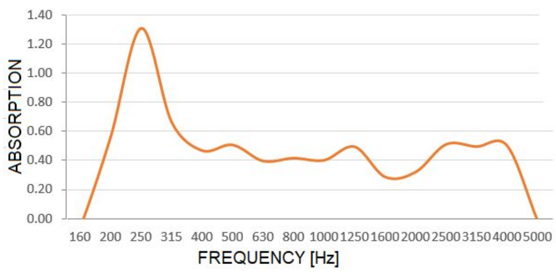

Figure 37. Absorption coefficient for designed Resonator (5 tubes)

6.3.5 Uncertainty

Uncertainty values are calculated using equation (14) for every measurement. Three curves are compared, one for each practice. Deviations shown correspond to typical uncertainties. For a 95% confidence value, a coverage factor of 2 has to be applied. Results are shown in Figure 38.

Maximum deviation values are found por Practice III measurement, In which case just one balloon was exploded, whereas, Practice I and II show similar deviations, using 12 balloons each.

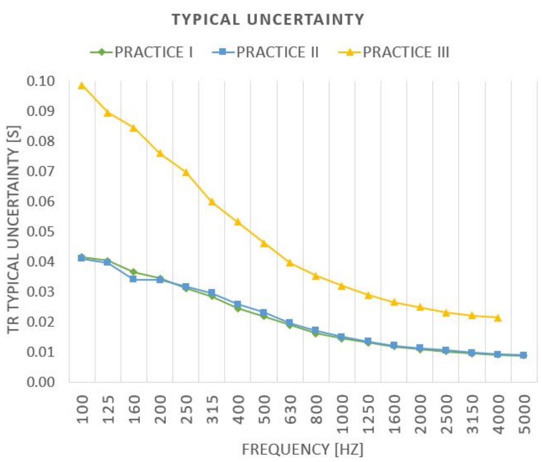

Figure 38. Typical uncertainty for T20 Measurements

Maximum deviation for every measurement is 0.10 s; which corresponds to an expanded uncertainty of 0.20 s for T20 analysis. Practices using the recommended amount of measurements show a significantly lower expanded uncertainty: 0.10 s. In any case, low frequency bands show higher uncertainty levels than high frequencies. Deviations for this last range can get as low as 0.01 s. It is concluded that following ISO 354 Recommendations, lowers the uncertainty levels considerably.

7. CONCLUSIONS

In this research work it is possible to see that the resonance frequency measured in every practice approximates to the one calculated theoretically. The difference observed is mainly due to irregularities in the samples, which generates turbulence and increases the acoustical mass and thus raises the resonant frequency. In Practice I, results show that the absorption is augmented by the increment of apertures and porous material. This is comparable to the research done by Valtonen [6] when he states that the most absorptive condition of a resonator is when the air cavity is full of mineral wool, since more absorptive material is added in the mentioned practice. In Practice II a clear increase in the absorption coefficient as the samples separate can be seen. This relates to the increase of sample surface due to the appearance of more edge area. Lastly, in Practice III results show that for a lower number of samples the absorber is more selective, and as the number of samples increases the selectivity decreases due to the add of resistive porous material. This is comparable to the research done by Daniel [9] as he states that absorption coefficient for a small area of an acoustical material is much greater than for a very large one, due to the diffraction phenomenon involved. The most interesting thing about this type of work is the union of a creative design with the efficiency of a good theoretical approach. In addition, this type of practices are essential to finish settling several theoretical concepts.

8. REFERENCES

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[4] Ingard, Uno. "On the Theory and Design of Acoustic Resonators". (1953)
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[8] Higgins, C. Orlowski, R. Gomez-Agustina, L. "An investigation into the Helmholtz resonators of the Queen Elizabeth Hall, London". (2016).
[9] Daniel, Eric. "On the Dependence of Absorption Coefficient upon the Area of the Absorption Material". (1960).
[10] UNE-EN ISO 354 :2004, "Medición de la absorción acústica en una cámara reverberante" (2004).

9. QUESTIONS

1) Is the room's RT standard deviation into the boundaries established by ISO 354?

Figure B shows the measured standard deviation values in the enclosure. The maximum value corresponds to 100 Hz, which is 0.04, while the standard suggests that the value for this frequency should be 0.05.

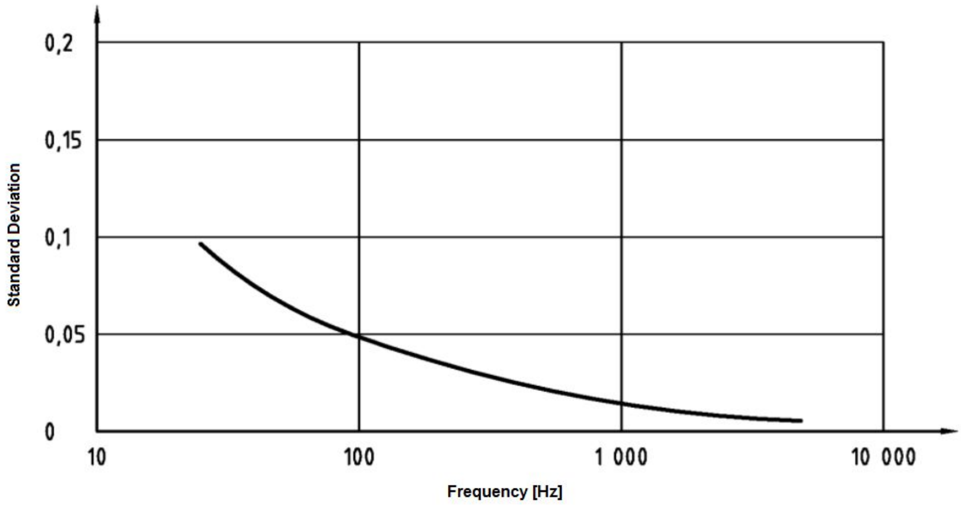

Figure A. Suggested Standard Deviation (ISO 354).

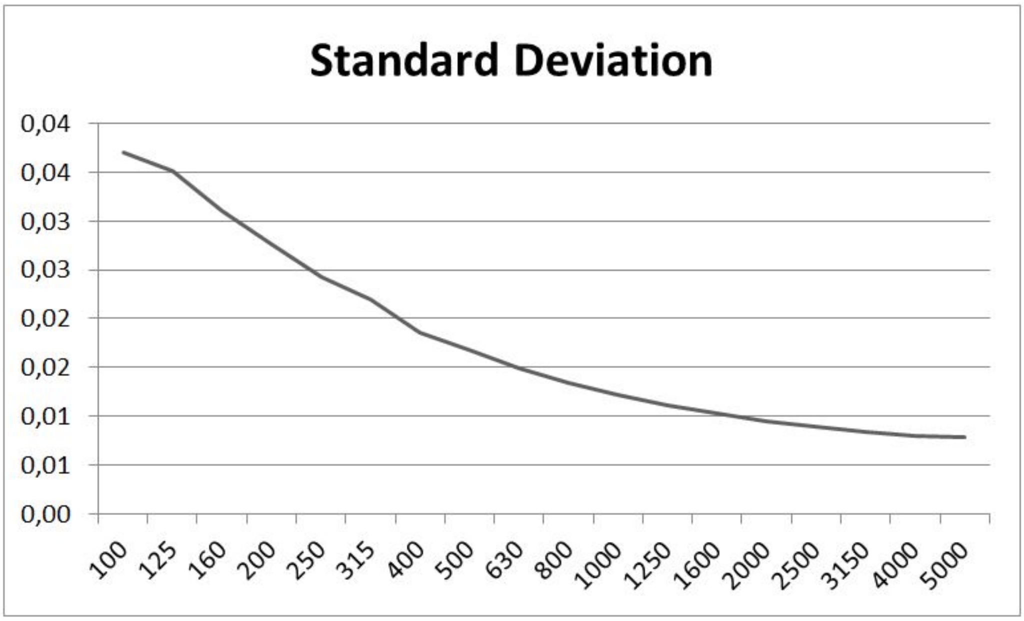

Figure B.Measured Standard Deviation.

2) How you may know if the modal density of the room is good enough for making absorption measurements? What does the modal topographic density establishes? (When making reverberant room measurements)

The values of the modal density depend on the geometry and the dimensions of the enclosure and, in general, its determination is very complex. Currently, in acoustic of enclosures, several methods are used to determine the modal density of a room. First, the Rayleigh equation is used, which has the characteristic of calculating the less predictable frequencies, behaviour wise:

$$f(n_x, n_y, n_z) = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$$

Where c_0 is the speed of sound, l_x, l_y and l_z represent the dimensions of the enclosure in metres, and n_x, n_x, n_x can take any value belonging to the natural numbers.
In relation to the volume of the enclosure and its reverberation time, the Schroeder formula is used:

$$f_0 = 2000\sqrt{\frac{RT}{V}}$$

Where RT is the reverberation time and V the volume of the enclosure.
The number of proper modes is unlimited, and the presence of all of them causes at each point a concentration of energy around the different modal frequencies, which gives a characteristic sound to each room, that is called coloration. Both of the equations previously mentioned allow to calculate the frequency for which useful information in a measurement can be obtained. Therefore, any information below that frequency might not be valid.

3) Why do you think Sabine's model is applied in ISO 354? Explain.

Reverberation time formulas are statistical models and are only applicable when there are a large number of reflections and the field is sufficiently diffuse. Sabine's equation is one of those models, and as one of the requirements of standard ISO 354 is that the enclosure should be sufficiently diffuse, using said expression is coherent, as long as an analysis is made for higher frequencies than Schroeder's.