DESIGN OF A NUMERICAL GENESIS DIFFUSER FOR A CHURCH

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This report presents the development of the design of a one dimensional curved numerical diffuser for a 14882 m3 church for use as a worship hall and organ concert hall. The design of an overlapping QRD 7 diffuser with a seamless surface, extending its maximum working frequency above 20 kHz, was carried out. Each section of the diffuser has a width of 165 cm, and a depth of 24 cm with a minimum working frequency of 250 Hz according to simulations performed in AFMG Reflex.

Keywords: diffusers, church, design, QRD 7.

1. Introduction

A diffuse sound field has a uniform angular distribution of sound energy flow at any point in space, making the distribution of acoustic energy uniform. This phenomenon has the effect that the listener cannot perceive the position of the source and is generated by non-specular reflections on the surfaces of the enclosure, so, to generate this property in the same, it is necessary to perform the correct design and acoustic treatment on the surfaces of the same. Acoustic diffusers are used to achieve this effect, the energy of the reverberant field will reach the ears of the audience equally from all directions throughout the space of the room, which will contribute to create a surround sound and, therefore, to increase the degree of existing spatial impression, improving the acoustic quality of the enclosure.

For the design of a diffuser the main objective is to obtain a surface capable of reflecting an incident wave in all directions (scattering). A diffuser consists of a series of slits, where each slit behaves as a sound source, but with a delay equal to twice its depth, then the problem is limited to find what should be the sequence of depths so that the diffraction pattern of the structure is as uniform as possible.

The objective in this report is to design a diffuser to be installed in a church with a capacity of 1200 people. The church has a volume of 14882 m3. Figures 1A and 2A are attached detailing the shape and dimensions of the church. The diffuser will be placed on the back wall of the enclosure, which has a surface area of 280.2 m^2.

This type of diffuser is based on a series of parallel cavities with a fixed width and different depths, generally separated by rigid dividers to prevent them from vibrating and causing resonance losses. In practice they are the most widely used in the whole field of acoustics because they are the simplest to develop and with good diffusion results. [5]

From the listening point of view, the effect achieved is that the same acoustic signal arrives at the same point outside in space from different directions, this is a contribution to the quality for listening, but its main disadvantage is that the arrival of these signals is out of phase, so it happens constructive and destructive sums. To minimize this effect it is necessary that the location and the polar pattern with which the signals reflect the different points of the diffusion surface have a high degree of randomness. To achieve this, the autocorrelation of the surface can be verified; the higher the autocorrelation, the worse the diffusion effect of the surface. So the cavity depths are obtained from a mathematical sequence, forming repetitive structures that produce diffusion of the impinging sound.
According to the known theory, the frequency limit to be treated based on the frequency spectrum of the different types of source to know the optimum dimensions of the diffuser cells. Being the maximum frequency calculated by Equation 1.

$$f_{máx}=\frac{c}{2w} \tag{1}$$

where c is the speed of sound and w is the width of the cells. With
the minimum frequency calculated by Equation 2:

$$f_{mín}=\frac{S_{(máx)}\,c}{2Nd_{máx}} \tag{2}$$

Where:

$$Sn=n^2\ módulo\,N \tag{3}$$

$$d_n=\frac{S_n\lambda_0}{N} \tag{4}$$

Figure 3A in Appendix shows the profile of a numerical diffuser and the parameters w and .d_n
Frequency limits will be taken into account based on the use of the venue. In this case it is a church used as an organ concert hall. It is important to consider the frequency spectrum of the spoken word and to take into account the intelligibility of the spoken word, and in turn the spectrum of the organ. Due to the importance of the intelligibility of the spoken word in this type of room, a slatted resonator (Helmholtz) is used. It consists of a series of slats of thickness D, at a distance from the wall d, and with slats of width w, in order to leave a closed air cavity between the two surfaces. The scheme is shown in Figure 1.

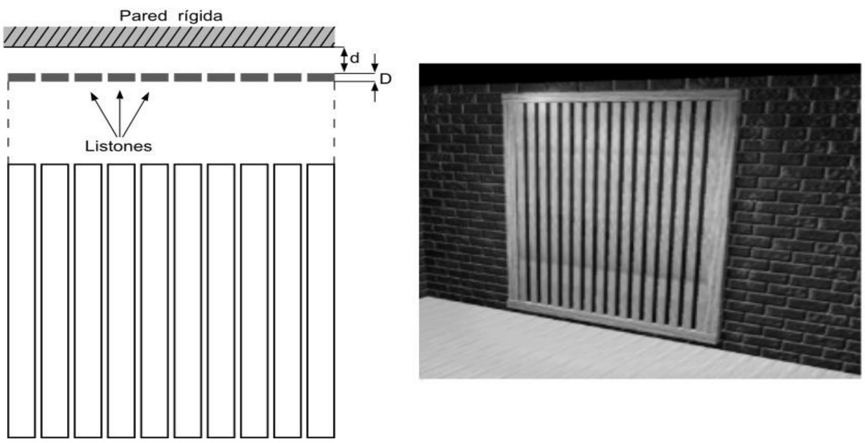

Figure 1. Slat Resonator.

The resonant frequency$f_0$is calculated by Equation 5.

$$f_0=5002\sqrt{\frac{r}{Dd\,(r+w)}} \tag{5}$$

With r the spacing between slats, D the thickness of each slat, d the distance from the wall to the slats, and w the width of each slat.
Finally, the randomness of the QRD 7 design is analyzed using the autocorrelation quality factor. As the autocorrelation factor increases, it indicates that the autocorrelation of the sequence increases. The corresponding code to calculate it will be attached in the appendix.

2. Procedure

2.1 Diffuser dimensions

Knowing the spectrum of the spoken voice, and analyzing the speech intelligibility and its main indicator SII (Speech Intelligibility Index), it is necessary to keep in mind that this diffuser must have enough absorption to attenuate the middle frequencies ranging from 1 kHz to 4 kHz, to decrease the TR60 in those bands, and thus increase the SII.
With the analysis of Figure 3, a curved numerical diffuser QRD 7 is set as a target. The choice of this diffuser is strongly linked to its production cost, ease of assembly, and dimensions that allow assembly by construction personnel. The design is modified with respect to the classic design, which corresponds to Figure 2, and sections are added so that the surface does not have discontinuities. The purpose of this modification is linked to the need to extend the maximum working frequency without the limitation of Equation 2, which imposes a cell width of 2 cm if a diffuser working up to 8 kHz is sought. To evaluate the surface design, simulations are performed in AFMG Reflex using the boundary element method.
Regarding the maximum depth, this value will not depend on the frequency from which it is intended to work, since the frequency spectrum of the organ starts at 20 Hz. It will depend on space limitations and ease of construction. A maximum depth of 24 cm was determined. The initial frequency will be calculated according to Equation 2 and compared with simulations. This does not mean that the diffuser will act only at these limits, there is a residual response above and below these limits. These limits are established to make the design, to know its behavior in relation to the frequency it should be measured.

3. Results

3.1 Design

The maximum frequency is calculated by means of Equation 1 and the design frequency by means of Equation 2. The results are presented in Table 1.

Table 1. Theoretical results of diffuser design.

Maximum frequency $f_{máx}$	1146.66 Hz
Design frequency f_0	250 Hz
Width a	15cm
Max. depth $d_{máx}$	24cm
Length l	1,65 m
Number of slots N	10

Due to the need to raise the maximum frequency, a curved diffuser was designed. The design objective was to curve it as much as possible without complicating its construction. Figure 2 shows a view of the diffuser shape.

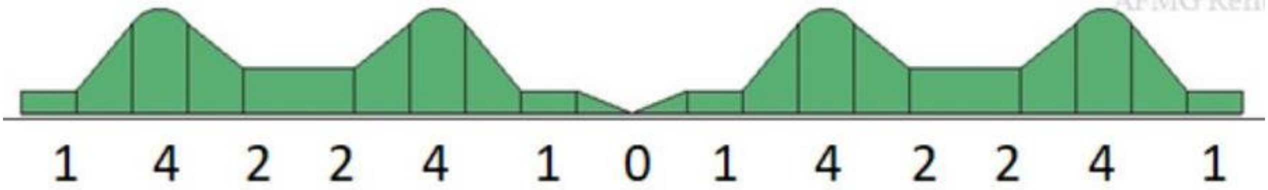

Figure 2 Curved diffuser and QRD 7 sequence.

The scattering and diffusion coefficient of the designed diffuser were evaluated by simulations in AFMG Reflex. The graph is presented in Figure 3.

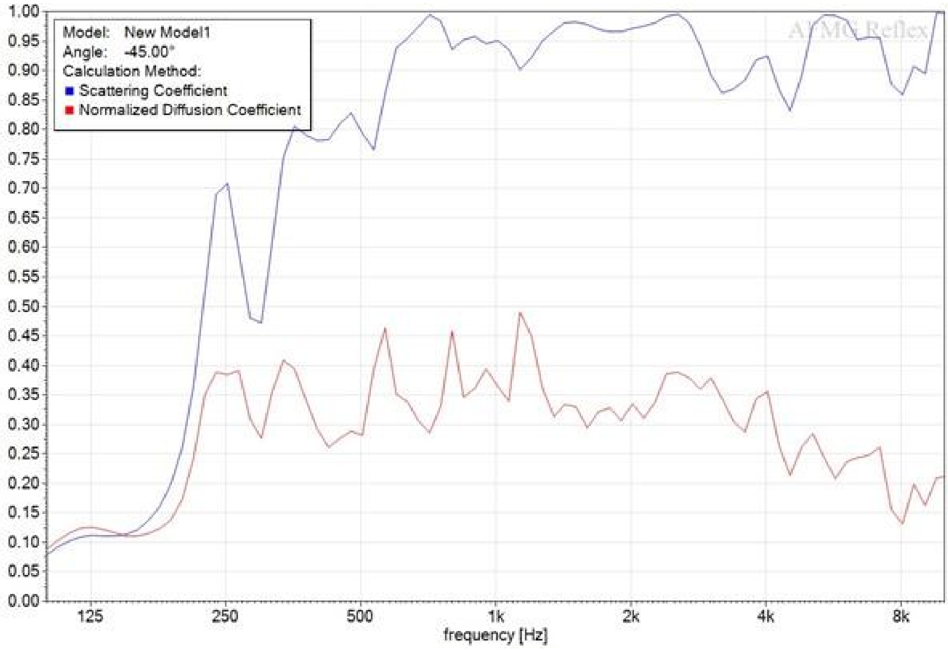

Figure 3. Scattering and diffusion coefficient graph.

The rest of the simulation results are presented in Annex 1. Simulations corresponding to other dimensions for the width of the diffuser sections and shapes are also attached.
Regarding the final absorption of the design, it is also necessary to analyze the room in which the equipment is going to be installed, and the above mentioned regarding the IBS. Therefore, the central absorption frequency will be close to the 2 kHz octave band, and absorbing material will be used to reduce its selectivity, so that the system can work in a wider frequency spectrum.
Although current theory does not allow precise calculations of the absorption coefficient as a function of frequency, approximations can be made according to design issues and comparison with previous measurements according to the literature consulted. Where, for example, it can be seen that the placement of the absorbing material on the wall considerably increases the bandwidth of the system. As shown in Figure 4:

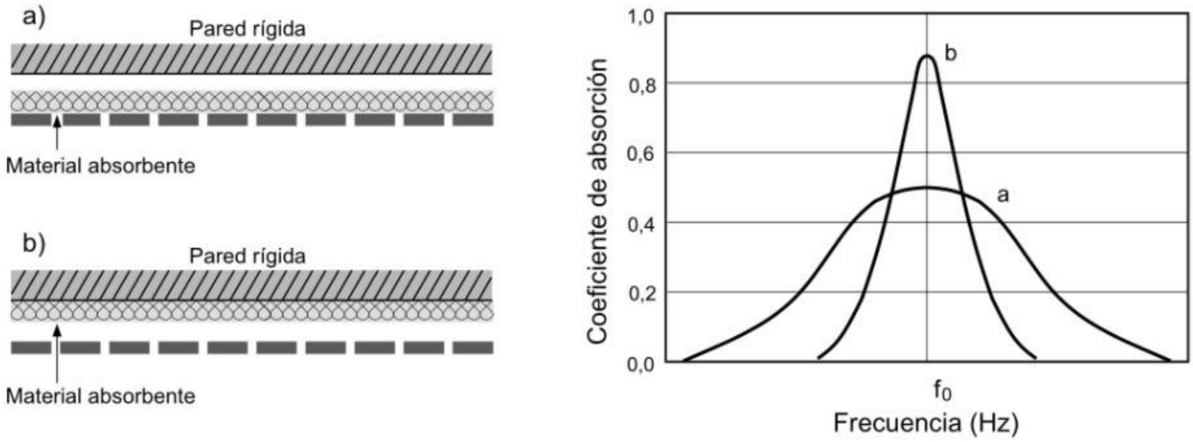

Figure 4. Expected generic absorption coefficient of a Helmholtz resonator as a function of the position of the absorbing material, a) against the panel, b) against the wall.

To calculate the center frequency at which the absorber works, it is first necessary to obtain the distance between the slats and the wall, for this an apparent d is used, which will be an average value of the diffuser depth. So d = 13.6 cm. The thickness of each slat to be used is linked to the materials available on the market. 1.5 cm is the thickness selected, both because of its availability and because it is a value that does not compromise the mechanical strength of the slat itself. Finally, it was decided to define w in 10 cm, leaving an r of 6 mm to define the central frequency of 2,040 Hz.

The material created in EASE for this simulation is as follows:

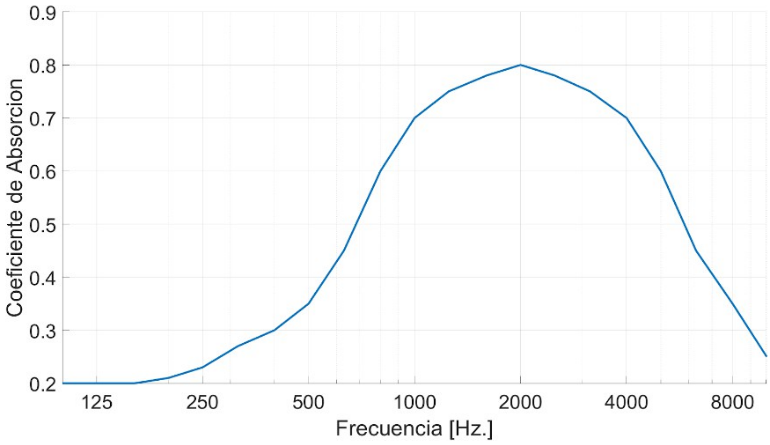

Figure 5. Diffuser absorption coefficient, with center frequency at 2 kHz.

3.2 Simulation in EASE

The simulated enclosure gives the following TR results by Sabine's method:

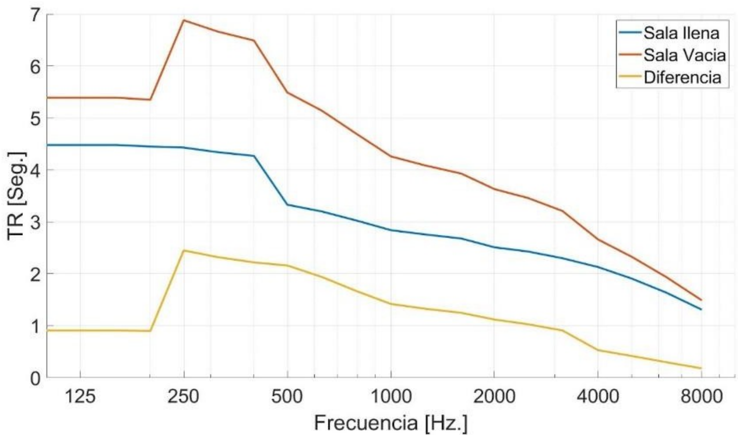

Figure 6: TR calculated by Sabine in EASE 4.3.

Where it can be seen that the difference between full and empty room is very high, especially at low frequencies.

3.3 Autocorrelation quality factor

For the sequence QRD 7, the autocorrelation quality coefficient is 0.6219, which is a very good value for estimating the diffusion of that sequence. But to place a sequence like the one in Figure 2 (which corresponds to 2 QRD 7) the factor worsens to 0.8831. Finally, when evaluating the complete surface of the back wall of the enclosure, which has a total of 10 diffusers as shown in figure 2, the quality factor increases to 2.911. Which is a very high value, but it must also be considered that the sequence is short, and covers a large area. It remains to evaluate and compare QRD 7 with another sequence such as QRD 11, which has an autocorrelation coefficient of 1.33. In this case, if a 30 m diffuser were used to cover the enclosure wall, a quality coefficient of 3.26 would be obtained. In the case of QRD 13, it has a quality factor of 3.27. So the choice of the sequence is the best, if this factor is taken as the only criterion.

4. Conclusions

The theory of the Helmholtz resonator system is approved by the literature, so the calculations for the resonant frequency of the system are expected to be correct, but the theory for the design of a resonator with absorption needs to be developed in order to be able to make a prediction with a higher degree of certainty. This is most likely linked to the fact that there are too many variables that are incorporated into the resistive material, such as its ability to absorb mechanical vibrations, the density of the material, its tortuosity and porosity. All these characteristics influence the response of the resonator system.

Although a real device was not measured in this work, errors are to be expected, since the equations do not take into account the introduction of a dissipative element, such as glass or rock wool. In addition, the literature consulted concludes that the position of the dissipative element has a direct impact on the variation of the absorption coefficient as a function of frequency, a quality that was used for the design of this work.

With the processing capacity available today, it is an interesting proposal to perform simulations of these systems by finite element methods.

On the other hand, the design of this diffuser does not seem to have a high associated cost, since making a module of this diffuser requires an MDF sheet of 1.83 m by 2.60 m, a standard size in the market. In addition, the rock wool to be used is of low density, and the lowest thickness that can be

The lowest thickness that can be obtained, which is 50 mm for the products offered by ISOVER, so that the condition of placing the absorbent material against the wall can be fulfilled, in order to widen the working bandwidth of the resonator.

In addition, the results for 5 cm and 30 cm wide sections are included in the appendix. Analyzing both simulations, it can be concluded that the minimum working frequency of the resonator is not only a function of the depth of the resonator, but also depends on the width of the section. Another characteristic that can be observed is that a narrow section, such as 5 cm, generates a large variation of diffusion and scattering values between one third of an octave and the next one. By increasing the width of the sections, this quality improved considerably, the choice of a section width of 15 cm over 30 cm is related to the final size of the device that would have a final width of 3.30 m, which makes it difficult to manufacture and assemble.

The introduction to the QRD diffuser of the continuous surface, and of a round section, generates that there are no lobulations in the polar pattern of diffusion. This can be seen in the figures in Annex A5, A6 and A7.

The simulations performed in EASE show that it is not enough just to add a diffuser on one of the walls of the room, although the graph shows a slope that shows that the higher the frequency, the lower the TR, some other treatment is necessary. This TR is the one proposed by Sabine, but it is not a value that would exist if measurements were taken at any particular point in the room. From what can be extracted that having a single wall, with a high degree of diffusion seems not to be linked to the concept mentioned in the introduction of the document, in which it is proposed that an environment is diffuse if at any point of it the energy comes from all directions. Therefore, the correct design of a diffuser does not have to be linked to the fact that the room where the diffuser is located is a diffuse room, or a room with a high diffusion property.

Finally, the choice of the QRD 7 sequence turned out to be the correct one. As for the autocorrelation quality factor, this sequence turned out to be better than others. But it was also taken into account that the design is feasible, and that it can be assembled by people, without complex assembly, minimizing assembly and assembly errors.

5. References

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6. Appendix A

6.1 Figures

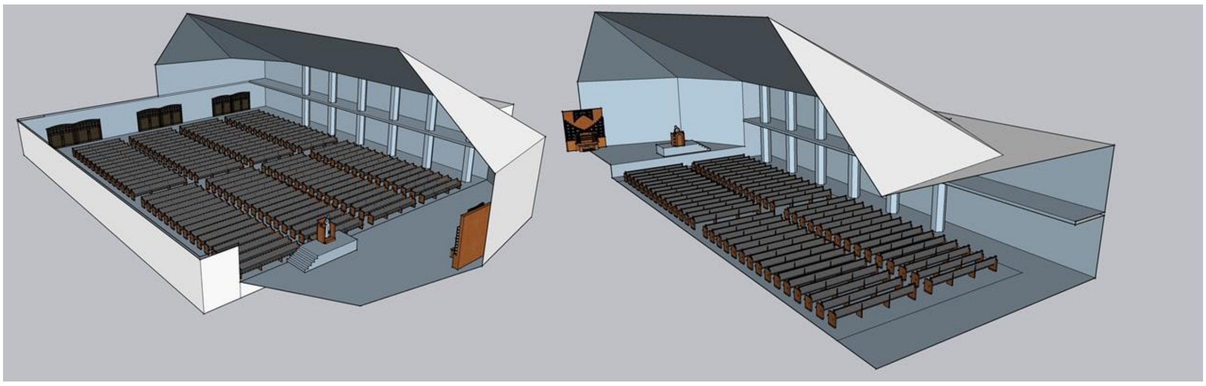

Figure A1. Views of the three-dimensional model from the stage (left) and from the entrance (right).

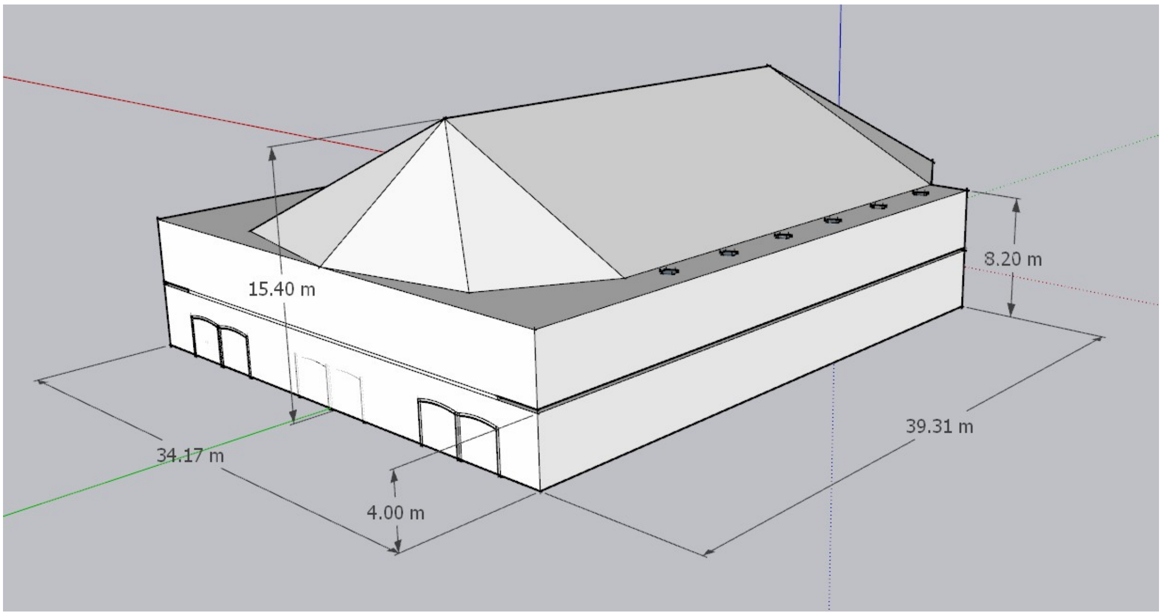

Figure A2. Exterior view and detail of dimensions.

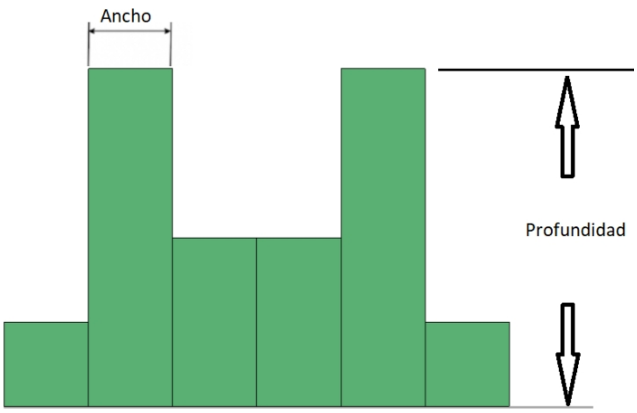

Figure A3. QRD 7 numerical diffuser.

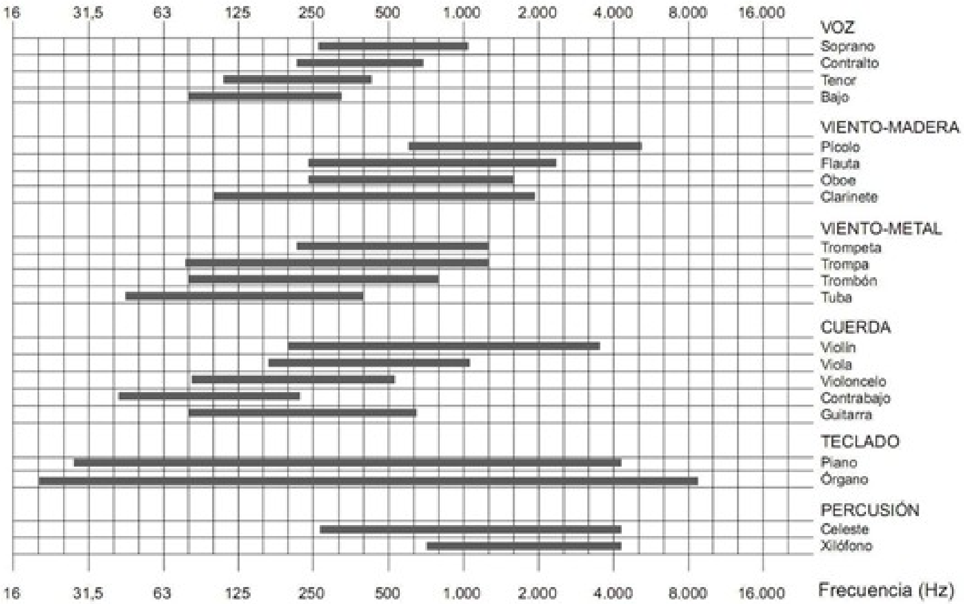

Figure A4. Frequency spectrum of different types of voices and instruments [3].

6.2 Spatial response plots

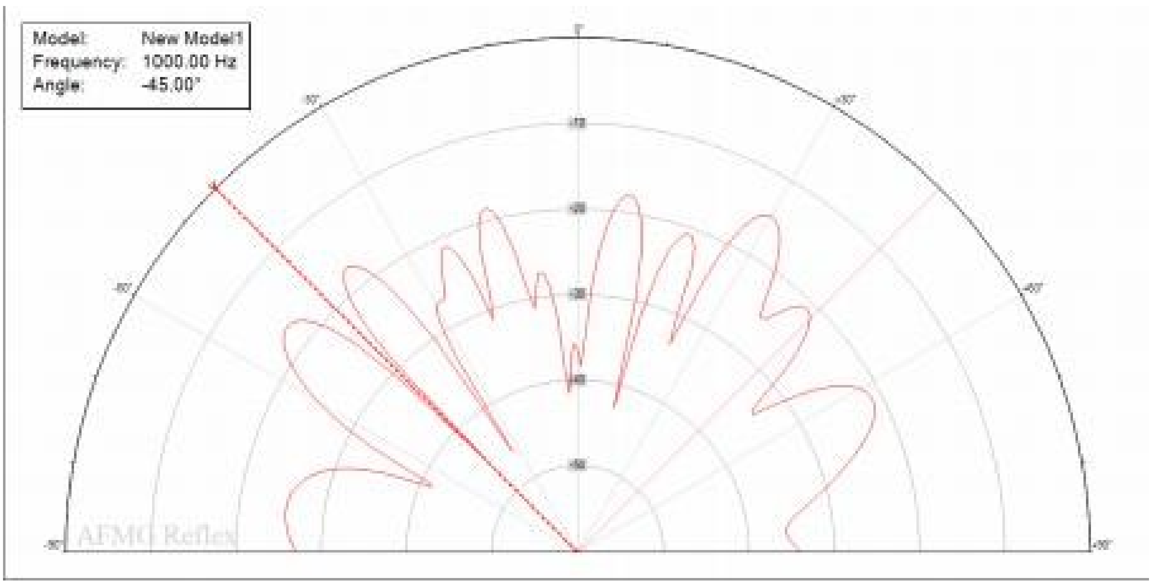

Figure A5. Spatial response at 1kHz

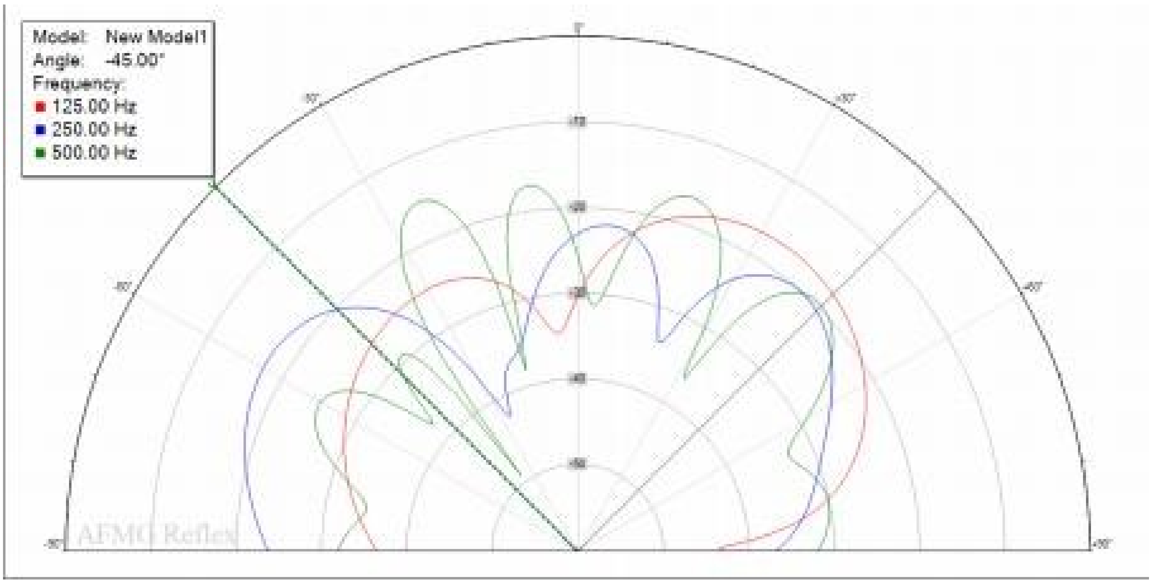

Figure A6. Spatial response at 125 Hz, 250 Hz and 500 Hz.

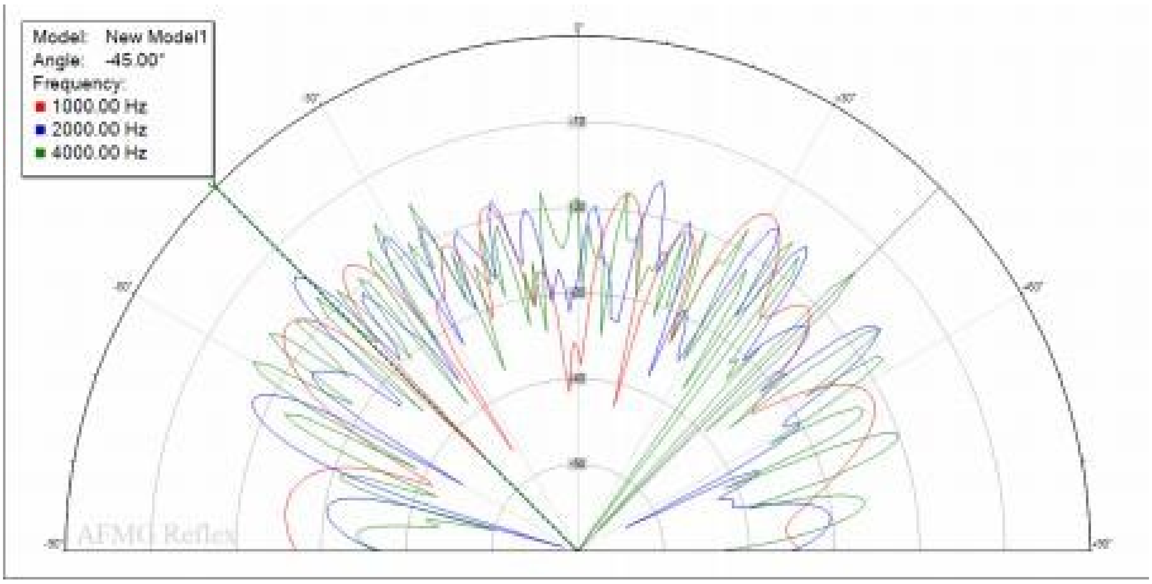

Figure A7. Spatial response at 1000 Hz, 2000 Hz and 4000 Hz.

6.3 Plots of scattering and diffusion coefficients.

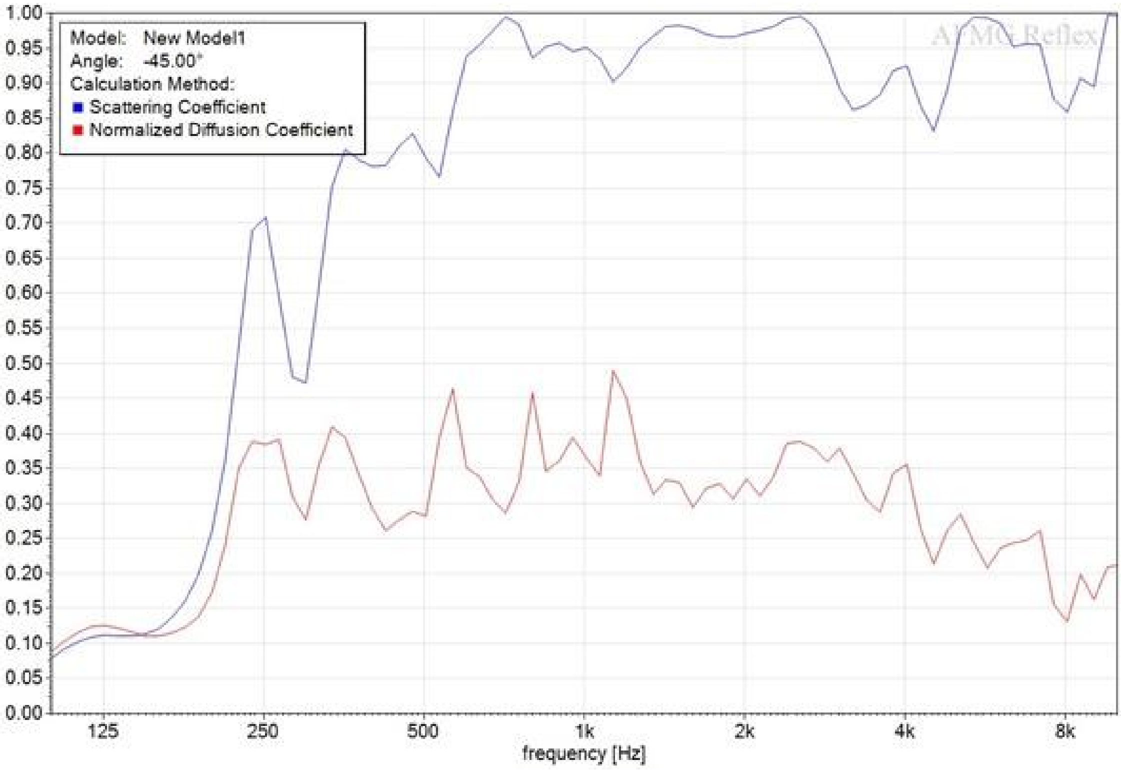

Figure A8. Coefficient of scattering coefficient and diffusion coefficient.

1.1 Observation comparing the width of the cells, keeping the diffuser depth constant.

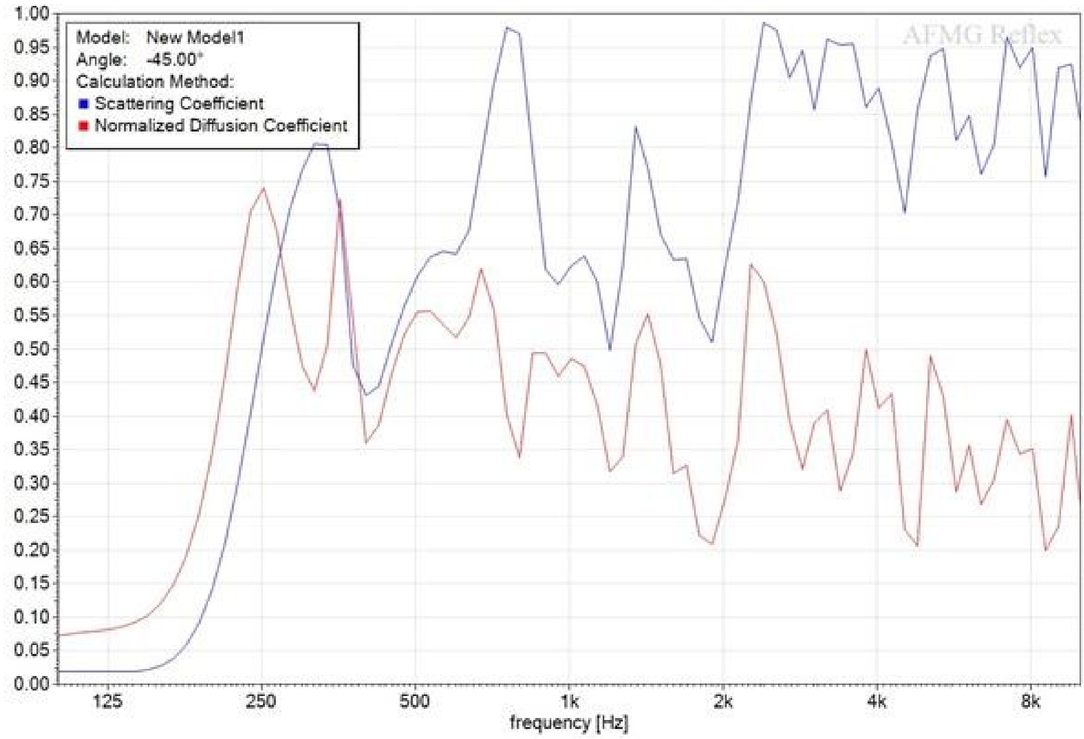

Figure A9. Scattering coefficient and diffusion coefficient for a cell width of 5 cm.

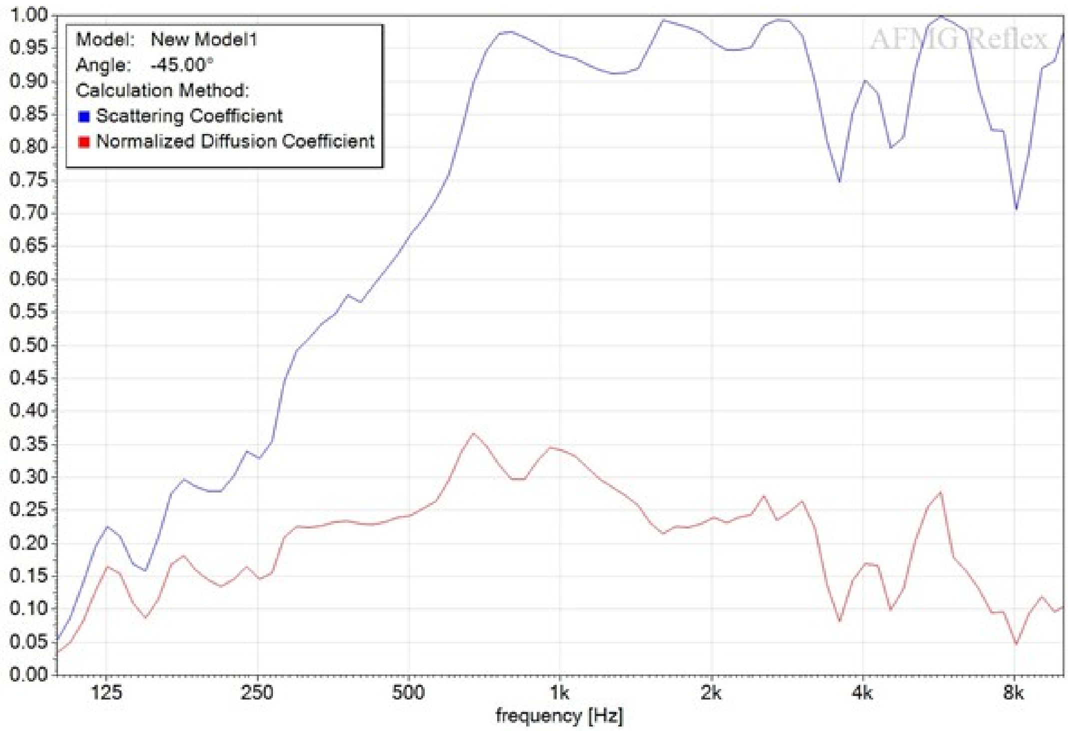

Figure A10. Scattering coefficient and diffusion coefficient for a cell width of 30 cm.

6.4 Code to verify the autocorrelation quality factor of a sequence.

```
Program to calculate the AUTOCORRELATION in 1D of a surface
and a Factor of Merit, FM;
%Enter a square matrix of integers representing the %depths of the unit
%depths of the diffusing unit. a=input('enter 1D
vector to evaluate');
[ACF,lags,bounds]=autocorr(a, [],2);
ACQF=10*(log10(sqrt(sum(ACF.^2))));%ACF is the sequence quality
descriptor;
autocorr(a)%Plots the autocorrelation;
'AC Quality Function (ACQF) =';%displays the name of the autocorrelation
value descriptor;
ACQF
The AUTOCORRELATION QUALITY FACTOR - ACQF - expresses with '0' the
highest possible autocorrelation given an autocorrelation function. The
%lower the ACQF value, the better the numerical sequence to be %applied in
a 1D diffuser.
```