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INFLUENCE OF THE MATERIAL IN THE ACOUSTIC PERFORMANCE OF OPTIMIZED RBF-BASED SHAPE DIFFUSERS

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ABSTRACT

Sound diffusers are currently a widely used solution in critical listening rooms, in order to reduce specular reflections without introducing excessive sound absorption. There are several types of diffusers on the market, although the most common are derived from the pioneering work of M. Schroeder in this area almost four decades ago. However, the optimization of diffusers' design has been a topic of intense research in the last years. The authors, in previous works, proposed an alternative technique to define new shapes for efficient sound diffusion, based on the use of radial basis functions (RBF) and, using a genetic algorithm, optimized those curvilinear surfaces, maximizing the diffusion coefficient and, at the same time, obtaining organic and more visual appealing acoustic devices. This parameter is computed within the optimization procedure using the Kirchoff integral equation and the Boundary Element Method (BEM).

In this work, some solutions developed according to the proposed methodology are presented and the experimental evaluation of some prototypes is carried out, in accordance with ISO Standard 17497-2: 2012, in order to evaluate the influence of the constituent material of the different prototypes. The experimental results are compared with the numerical results obtained in the optimization process.

Keywords: Sound diffusers, Organic surfaces, Optimization, ISO 17497-2: 2012
I-INCE Classification of Subject Number: 25, 72, 76

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1. INTRODUCTION

Sound diffusers are a common technical solution used in the last four decades for conditioning performance rooms with greater acoustic requirements, such as theatres, concert halls or auditoria. They are applied to enrich the sound field in the performance spaces without presenting too much sound absorption, while scattering the sound energy uniformly around the room [1]. In order to achieve proper sound diffusion, the surfaces of the room can be shaped, surface ornamentation can be used and/or specific elements can be adopted, on the walls and ceilings, like sound diffusers.

A significant number of the acoustic diffusers commercially available are based on the phase grating diffusers or Schroeder-type diffusers. These are obtained by a series of adjacent wells of the same width, separated by thin walls, whose depths can be defined by a (simple) mathematical number sequence, *e.g.* a sequence of quadratic residues, being known as quadratic residue diffusers (QRD), among other Schroeder diffusers. However, in some particular cases, the visual appearance of the acoustic conditioning of the room with QRDs is considered by architects to be unaesthetic or visually unattractive in modern spaces [1], and thus other geometrical forms of the diffusive surfaces or elements need to be customized and explored.

Although there are already some methodologies for the development, modelling and optimization of diffusers, the authors presented in previous works [2,3] a methodology for the design of more organic (*i.e.*, curvilinear) surfaces, which could be aesthetically more appreciated and better accepted, and are optimized to uniformly disperse the sound incident in them. Thus, in these works, the authors have demonstrated the possibility of developing innovative acoustic diffuser solutions with maximized acoustic performance, whose shape is generated by the use of Radial Basis Functions (RBF) and which are based on modern numerical modelling techniques like the Boundary Element Method (BEM) and optimization techniques, namely Genetic Algorithms.

In [4], an experimental validation of some solutions obtained through the proposed methodology was presented. Given the dimensional constraints of the DEC / FCTUC semi-anechoic chamber, among the various possible diffusers determined by the method presented in [3], the diffusers chosen were those whose optimization objectives could be observed in this laboratory - hence they were optimized to be used individually (optimization of only 1 module) and only for normal incidence (and not for 3 modules and 5 angles of incidence as referred to in ISO Standard 17497-2: 2012 [5]) but the proposed methodology allows the optimization for "n" identical modules and for several angles of incidence. Three prototypes were built in plywood, one optimized for the 1000Hz octave band, another optimized for 9 third octave bands in the middle range frequencies and another optimized for 9 octave third bands at high frequencies.

The main objective of this work is to experimentally verify if there is any influence of the material that make up the diffusers and their surface finish in the performance of the diffusers. For this purpose, EPS diffusers were produced, similar to those of plywood evaluated in [4]. In some of them, a fiberglass finish was applied to the surface. Thus, this work presents the experimental evaluation of the diffusion coefficient (according to the ISO Standard 17497-2: 2012 [5]) of 3 optimized solutions obtained by the method proposed by the authors (and presented in [2, 3, 4]) materialized in prototypes made of plywood, EPS and EPS coated with fiberglass.

On the next section, based on [2, 3, 4], the proposed method is briefly presented. And, then, the constructed prototypes are presented and the data obtained in the laboratory are compared with the results calculated numerically.

2. IMPLEMENTED METHODOLOGY

2.1 Definition of the geometry

In order to obtain "organic shapes", *i.e.*, smooth and curvilinear geometries with natural shape, the use of a set of mathematical functions called "Radial Base Functions" (RBF) was proposed as the basis of interpolation between a certain number of ***NC*** control points, themselves lying on the surface of the acoustic diffuser. Although there is a very broad set of functions of this type that could be used, the choice fell on MQ RBF (Multi-Quadrics) functions. These functions, like the generality of RBFs, depend only on the distance between a point of origin (RBF center) and a destination point, ***r***, and a free parameter, ***c***, taking the following form:

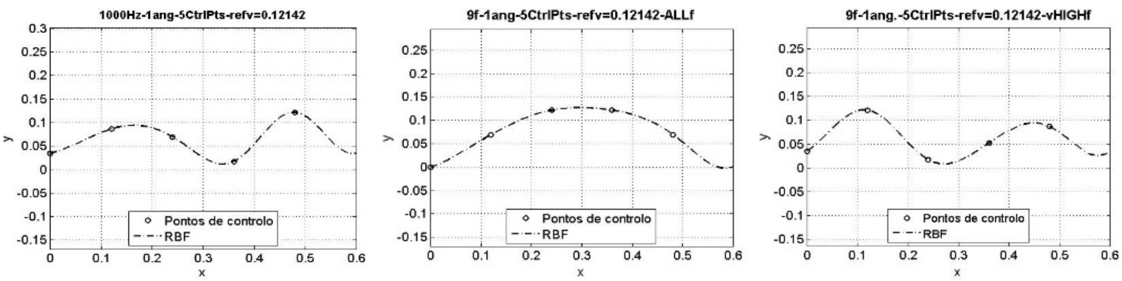
$$\phi_j(\underline{x}) = \sqrt{r^2 + c^2} \qquad (1)$$

Considering a number ***NC*** of control points, with (x_i, y_i), a possible interpolation scheme can be assembled using a set of ***NC*** RBFs, each one centered at one control point, such that:

$$\sum_{j=1}^{NC} A_j \phi_j(x_i) = y_i, \text{ for each } \boldsymbol{i}=1...\boldsymbol{NC} \qquad (2)$$

Applying Equation (2) to each collocation point, a system of ***NC*** equations on ***NC*** unknowns is generated, and its solution allows obtaining the amplitudes A_i of each RBF.

A schematic representation of the obtained interpolating curves for the 3 optimized diffusers used in this work is depicted in Figure 1. It should be noted that the definition of the diffuser shape is performed considering a pre-defined number of control points (in this work ***NC***=5 was considered), equally spaced through a fixed width (in this work ***L***=0.60 m), and which have only 2^3 possible ***y*** coordinate values, between y_{min}=0 and y_{max}=*refv* (*refv* being a user-specified value, for this work *refv* =0.121 m). Further details on how those curves were obtained can be found in [2, 3, 4].



a) *b)* *c)*

Figure 1 - RBFs curves resulting from the optimization for: a) f_{oit}=1000 Hz; b) 400 Hz < $f_{1/3oit}$ < 2500 Hz; c) 800 Hz < $f_{1/3oit}$ < 5000 Hz.

2.2 Sound Diffusion Coefficient

Sound diffuser performance is usually quantified by means of the Sound Diffusion Coefficient, d_θ, which gives an idea of the capacity of a diffusing device to spread sound energy in space. This parameter is evaluated from the polar scattering diagram of a given diffuser configuration, by means of the equation:

$$d_\theta = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{(n-1)\sum_{i=1}^{n}\left(10^{L_i/10}\right)^2} \tag{3}$$

To normalize this coefficient, it is compared with the diffusion coefficient of a flat plate with the same dimension (in this case length) of the diffuser under analysis. The purpose of this normalization is to remove the diffraction effects at the edges of the diffuser due to the limited size of the sample under analysis. The normalized diffusion coefficient is given by [5]:

$$d_{\theta,n} = \frac{d_\theta - d_{\theta,flat\_plate}}{1 - d_{\theta,flat\_plate}} \tag{4}$$

In the methodology proposed by the authors for modelling and optimizing the diffusers [2, 3], the analysis of the sound diffusers is performed numerically, and so the SPL, ($\boldsymbol{L_i}$), at different receiver positions are calculated using the Boundary Element Method (BEM). For more detailed information on the implemented BEM model, consult [2, 3, 6, 7].

2.3 Surface shape optimization algorithm

Given the above formulation and mathematical details, it is now important to define all the optimization procedure used to define the optimized organic diffusive surfaces. This optimization is based on the use of a Genetic Algorithm, and it is described in a simplified manner in the flowchart illustrated on Figure 2. At the end of this process, a final organic (smooth curve) shape is obtained, defined in terms of RBF superposition, with optimal performance for the selected frequency bands and angle of incidence.

Genetic algorithms are distinguished from other optimization methods by working with the coding of input parameters (and not with the parameters themselves), by operating a set of individuals (*population*) using a cost (or merit) function to classify them and to rely on probabilistic iteration rules (genetic operators: "*Selection*", "*Mutation*" and "*Crossover*") to make the *population* (solutions) evolve.

An initial population of *npop* individuals (diffusers) can be formed randomly (or it can be fixed) and the characteristics of each individual are determined by their genes. When designing diffusers, genes are simply a set of numbers that describe the surface: *control points* of the RBF. In the present work, since it was established that the control points are uniformly distributed along the width of the diffuser (by definition L = 0.6 m), the coding of each individual is only relative to the height ("***y***") of each of them. A 3-bit binary encoding was used to allow 8 levels (2^3 steps), ranging from "0" to a maximum value defined by the user (in this work *refv* =0.121 m).

Each individual (or the shape of the diffuser) has a value of fitness that indicates how well it performs in scattering the sound: the *sound diffusion coefficient*, which is evaluated, as referred to in the previous section, using BEM.

Through genetic operators, *selection, crossover* and *mutation*, the suitability of successive populations improved in the optimization iterative process.

This iterative process continues until a pre-defined limit of generations is reached (maximum number of iterations) or the population becomes sufficiently adapted, whose diffuser produced with the best shape does not change over several generations and thus can be classified as optimal.

In the end, the proposed optimization process leads to a smooth geometry, optimized for a given frequency band (or frequency bands), for one or more positions of the sound source and will allow maximum performance.

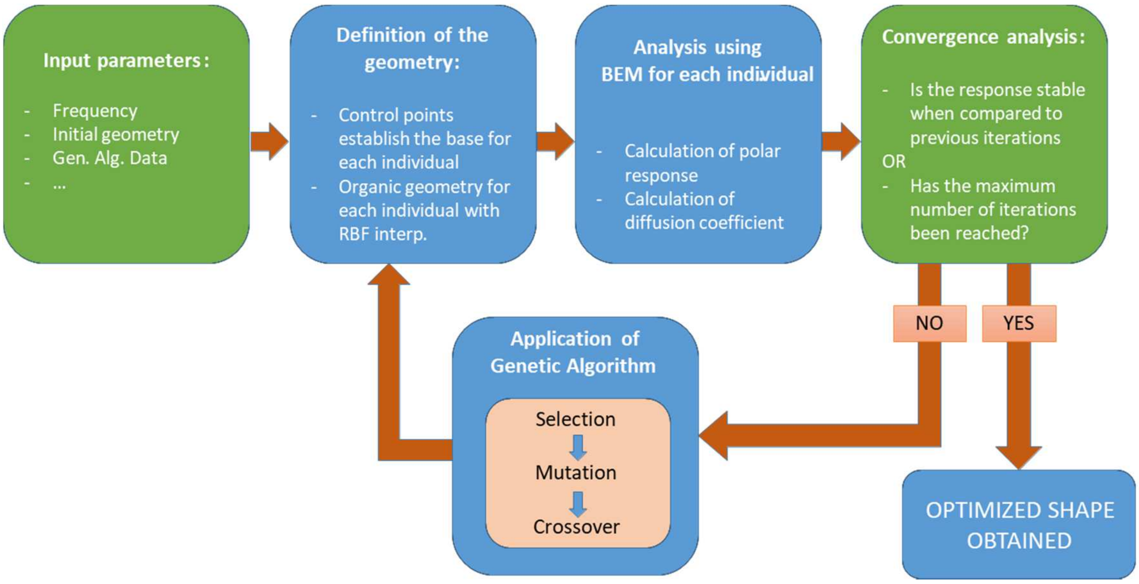


Figure 2 - Flowchart of the calculation/optimization process.

3. TESTED PROTOTYPES

3.1 Selected optimized shapes

The optimized curves chosen to produce prototypes are the same ones that were used in [4]. The performance of these prototypes were evaluated in the semi-anechoic chamber of the DEC / FCTUC, according to ISO 17497-2: 2012 [5]. Due to the dimensional restrictions of this chamber, diffusers that were optimized to be used individually (1 module optimization) were chosen and only for normal incidence (the proposed methodology allows to optimize for "*n*" identical modules and for several sound source positions).

On the other hand, since these prototypes are intended to evaluate the ability to manufacture future commercial products, it was decided to choose optimized diffusers whose end points have the same height and that the slope of the curves at these points is equal, in order to allow using several equal (adjacent) modules without discontinuities in the joint curvature thus defined.

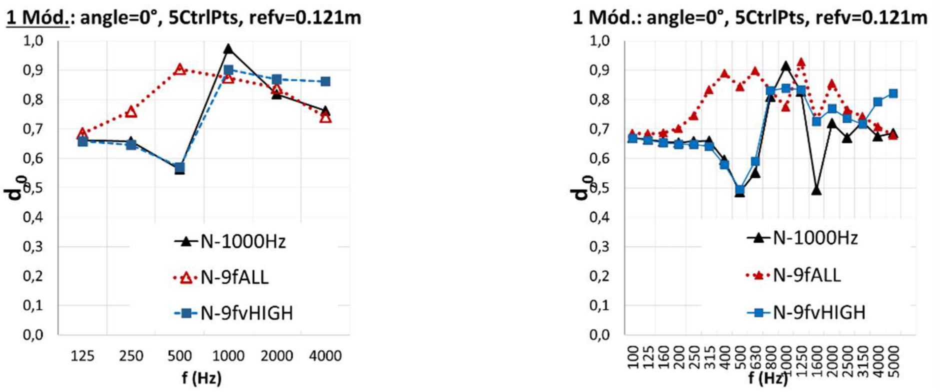
The width of the diffusers was ***L***=0.6 m since the standard size of the diffusers on the market is 0.6 m x 0.6 m. Only 5 control points were used because, as seen in [3], this is sufficient to obtain high diffusion coefficients. On the other hand, since the prototypes are also made of plywood [4], the use of more control points could give rise to too "wrinkled" surfaces that could hardly be manufactured in this material. The maximum possible height for the control points was ***refv***=0.121 m, since not very deep diffusers were aimed. As previously stated, the height of the control points was coded into 3 bits, allowing them to take 8 possible heights during the optimization process. From an initial population of 22 individuals whose ordinates of all control points were ***y***=0 m (flat surfaces), the optimized diffusers correspond to the "fittest" individual after 150 iterations.

The first diffuser to be chosen (***Figure 1a***) was one that was optimized only for an octave band (and for normal incidence) and whose maximum thickness was not very high. Thus, an optimized diffuser for the octave band centered at 1000 Hz was chosen. It is recalled that, in the optimization process for an octave band, only 5 discrete frequencies are taken into account for the calculation of the sound diffusion coefficient spaced within the frequency band [2,3]. The value obtained for this optimization parameter was $\boldsymbol{d_0}$=0.991. This diffuser will be called "***1000 Hz***".

The second diffuser chosen (***Figure 1b***) was one that, for normal incidence, was optimized for 9 bands of one-third octave in the medium frequencies, from the 400 Hz band to the 2500 Hz band. This optimization corresponds to maximizing the arithmetic mean of the value of the sound diffusion coefficient in each of the bands (which is obtained using 5 discrete frequencies equally spaced within the respective 1/3 octave band), to which the standard deviation is subtracted in order to value diffusers with a high average (of the sound diffusion coefficient), but with more constant values (lower standard deviation). The value obtained for this optimization parameter was $\boldsymbol{d_{average\_corrig}}$ = 0.797. This diffuser will be called "***9fALL***".

The last diffuser chosen (***Figure 1c***) results from the optimization of a diffuser for high frequencies. It was obtained by maximizing the weighted average of the sound diffusion coefficients in 9 one-third octave bands, centered from 800 Hz to 5000 Hz, whose weights in the 3150 Hz, 4000 Hz and 5000 Hz bands were respectively "6", "7" and " 8 ", and " 1 "on the remaining 6 bands. To this weighted average, it was subtracted the value of the weighted standard deviation with the objective of not only obtaining diffusers with high values of the sound diffusion coefficient at high frequencies, but these being more constant (lower weighted standard deviation). The value obtained for this optimization parameter was $\boldsymbol{d_{average\_corrig}}$ = 0.781. This diffuser will be called "***9fvHIGH***".

Figure 3 shows the diffusion coefficient obtained numerically for the 3 optimized shapes.



a) b)

Figure 3 – Sound diffusion coefficient obtained numerically for normal incidence: a) octave bands; b) 1/3 octave bands.

Analysing the numerical results obtained by octave bands (***Figure 3a***), it is clear that the assumptions of the respective optimizations have been reached. In fact, the diffuser "***1000Hz***", optimized only for the octave band centered at 1000 Hz, is quite effective in this frequency, better than the others; the "***9fALL***" diffuser, which has been optimized to have high values in the 1/3 octave bands in the mid frequencies (which correspond to the constituent bands of the octave bands from 500 Hz to 2000 Hz), taking into account not only their high value but also the lower dispersion of its values, has almost constant high values; The "***9fvHIGH***" diffuser, which has been optimized to have high and constant values in the 1/3 octave bands at high frequencies, also fulfils its objectives, being the most efficient diffuser in the octave band centered at 5000 Hz, however, it is high from the 1000 Hz band (fulfilling its objectives, since 800 Hz is the first 1/3 octave band that constitutes the 1000 Hz octave band).

The conclusions that can be drawn from the observation of Figure 3b) are not very different from the analysis of the results in octave bands. However, the following results are outlined: the "***1000Hz***" diffuser is clearly more efficient in the 1/3 octave bands constituting the 1000 Hz octave band than in the other bands; the "***9fALL***" diffuser, optimized for the medium frequencies, has high efficiency, it has some oscillations, however, the minimum values are not lower than 0.7 (and the standard deviation relative to the average between 400 Hz and 2500 Hz is 8,9%); the "***9fvHIGH***" diffuser, optimized for high frequencies, not only has high values but is fairly constant from 800 Hz to 5000 Hz (the standard deviation relative to the average is only 3.6%), being particularly efficient in bands of 4000 Hz and 5000 Hz, for which the optimization weighted higher than the other optimization bands.

3.2 Prototypes

For this work, we have used the prototypes of plywood (***Figures 4a***) constructed to validate the optimization methodology proposed by the authors in [2, 3] and presented in [4]. To investigate the influence of the density of the constituent material of the diffusers, three prototypes were constructed in EPS (Expanded polystyrene) with $\boldsymbol{m_v}$ = 25 kg/m^3 (***Figures 4b***).

a1) a2) a3)

b1) b2) b3)

*Figure 4 – Prototypes constructed. a#) Plywood; b#) EPS. Diffuser: #1) "**1000 Hz**"; #2) "**9fALL**"; #3) "**9fvHIGH**".*

To study the influence of surface finish, the surface of the EPS diffusers was covered with fiberglass – see Figure 5.

While remaining as faithful as possible to the RBF curves (despite possible minor construction errors), the surfaces were shifted so that, with respect to the diffuser base (y = 0.0 m), the highest point of each of the prototypes had a height of y = 0.15 m (total thickness of each prototype is thus 0.15 m).

a) *b)*

*Figure 5– a) EPS prototypes constructed: above EPS without surface finish, below EPS with fiberglass finish. b) Detail of the fiberglass finish of the diffuser "**9fALL**".*

4. EXPERIMENTAL PROCEDURE

The laboratory tests were performed to obtain the sound diffusion coefficient, for normal incidence, in accordance with ISO 17497-2: 2012 [5] and whose procedure has already been discussed in [6, 7]. The test configuration is briefly described (see Figure 6): the sound source is aligned with the center point of the diffuser (normal incidence), located 3.0 m away. The microphones are placed in a semicircle centered on the center point of the diffuser with a radius of r = 1.9 m. Measurements were made with an angular discretization of 10°, corresponding to 19 receivers. As stated in [6, 7], this configuration, for diffusers with a width of L = 0.6 m, allows to have more than 80% of the receivers outside the specular region, as it is required in the aforementioned standard.

a) *b)* *c)* *d)*

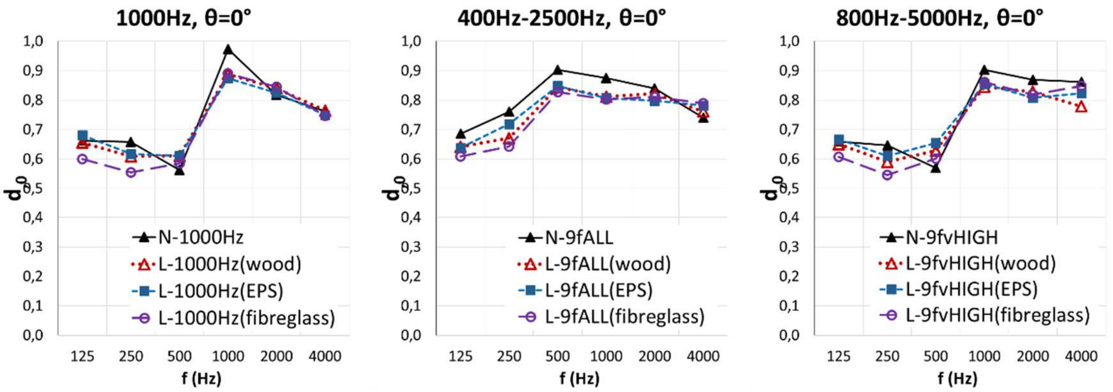
Figure 6 - Experimental procedure: a) Lay-out of the semi-anechoic chamber; b) Position of the prototype; c) Relative position of the sound source; d) Top view of the prototype under test.

According to [6, 7], in order to obtain the experimental sound diffusion coefficient it is necessary to perform an *FFT* on the difference between the impulsive responses "with" and "without" the diffuser (after using a temporal window that allows removing residual reflections that do not come from the diffuser being analysed). With the parameters used in the tests to obtain the impulsive responses it was possible to obtain a "*fine*" frequency discretization (impulsive responses were obtained through the *MLS* technique, with the maximum number of sequences defined by 2^{14}-1 = 16383, with a duration of 1.2794 s, which corresponds to a sampling frequency of 12806 Hz and a frequency discretization of less than 1 Hz, $\boldsymbol{\Delta f}$ = 1.2794^{-1} Hz) [7, 8].

In order to compare the results obtained in the laboratory ("**L**" in the legends of the following figures) with the numerical results ("**N**" in the legends of the following figures), the numerical diffusion coefficient had to be recalculated also taking into account a fine discretization in frequency (≈1 Hz) instead of using only five discrete frequencies, as it was done previously in the context of optimization. In the recalculation of the numerical results it was also noted that the laboratory results were obtained from 19 microphone positions and not 180 receivers, as used in the optimization process.

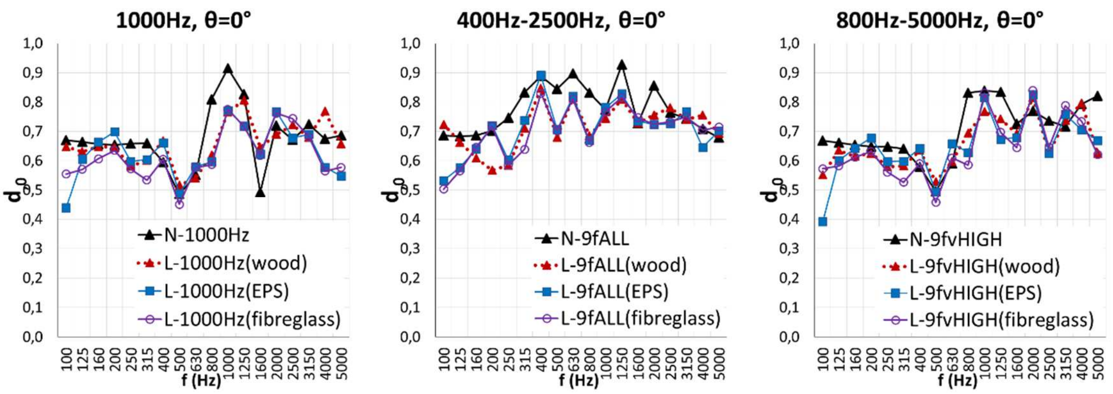
5. RESULTS AND DISCUSSION

The following figures present the comparison of the numerical results of the sound diffusion coefficient with the experimental results, in octave bands (***Figure 7***) and in 1/3 octave bands (***Figure 8***).



a) *b)* *c)*

*Figure 7- Comparison between numerical and laboratorial results of the sound diffusion coefficient for normal incidence, in octave bands (1-module evaluation): Optimized diffuser: a) "**1000 Hz**"; (b) "**9fALL**"; c) "**9fvHIGH**".*

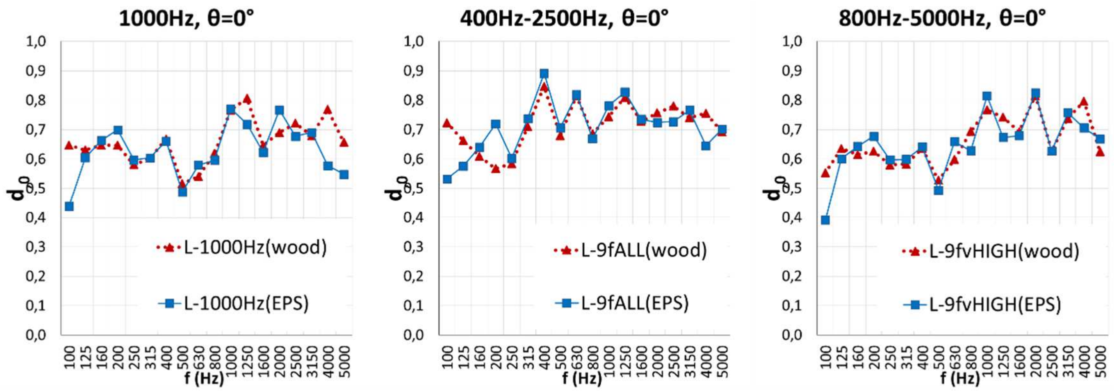


a) *b)* *c)*

*Figure 8 - Comparison between numerical and laboratorial results of the sound diffusion coefficient for normal incidence, in 1/3 octave bands (1-module evaluation): Optimized diffuser: a) "**1000 Hz**"; (b) "**9fALL**"; c) "**9fvHIGH**".*

Observing Figures 7 and 8, it can be concluded that there is a good agreement between the numerical results and the experimental data. In general, the experimental results are slightly lower, however, closely following the "trend" of the numerical results. Thus, it can be said that, although there is no absolute agreement in quantitative terms, there is a good agreement in qualitative terms. Therefore, it can be considered that these tests validate the optimization process proposed in this work and the conclusions drawn from it, namely those made in [2, 3, 4].

For a better analysis of the results, Figure 9 shows experimental results (in 1/3 octave bands) obtained for diffusers made of plywood and with diffusers made of EPS.

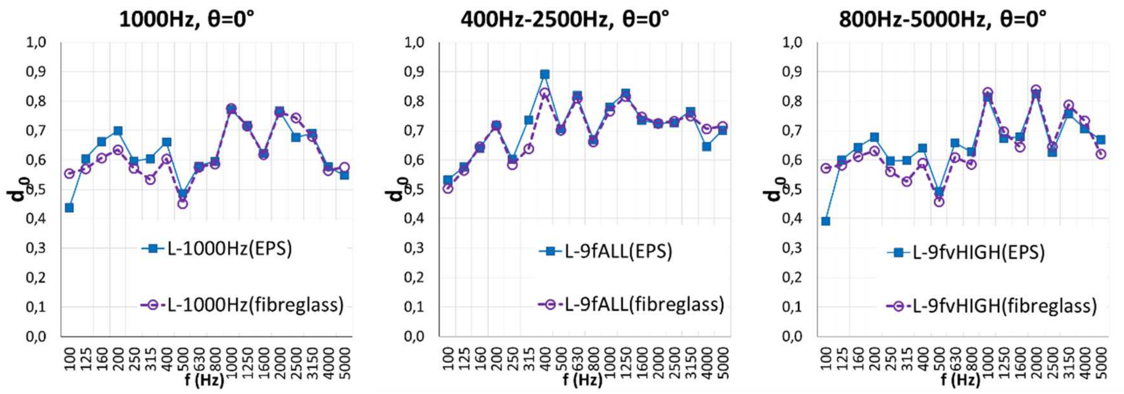


a) *b)* *c)*

*Figure 9 - Sound diffusion coefficient for normal incidence, in 1/3 octave bands (1-module evaluation). Comparison of diffusers of different materials, plywood versus EPS. Optimized diffuser: a) "**1000 Hz**"; (b) "**9fALL**"; c) "**9fvHIGH**".*

As it is easily observable, and contrary to what was expected, the results obtained indicate that there are no significant differences between the two diffuser material types.

In order to more easily observe the influence of the surface finishes of the EPS diffusers, Figure 10 presents the results obtained for these diffusers. Observing this figure, it is found that there is almost no influence on hardening the surface of an EPS diffuser with the fiberglass application.



a) *b)* *c)*

*Figure 10 - Sound diffusion coefficient for normal incidence, in 1/3 octave bands (1-module evaluation). Comparison of EPS diffusers with different finishing, EPS painted vs. fiberglass painted. Optimized diffuser: a) "**1000 Hz**"; (b) "**9fALL**"; c) "**9fvHIGH**".*

6. CONCLUSIONS

In work [3] the authors showed that the proposed methodology for the optimization of curved surfaces to provide high diffusion was efficient and in work [4] they confirmed experimentally their numerical results, testing 3 prototypes built in plywood. In this work, the objective was to study the influence of the density of the material constituting the diffusers and the correspondent surface finishing.

The results obtained indicate that the diffuser density is not significant in the acoustic performance and that EPS surface hardening (increased stiffness by fiberglass application) also has no significant influence.

These results allow to sustain that the use of EPS diffusers can be a good solution, from the point of view of the scattering of the reflected sound energy. However, their behaviour regarding sound absorption should also be studied.

7. ACKNOWLEDGEMENTS

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