Toronto, Canada
International Symposium on Room Acoustics
2013 June 9-11

ISRA 2013

Increasing Reverberation Time with Diffusers: a new acoustic design for more sustainable halls

Umberto Berardi (uberardi@wpi.edu)
CEE Dep., Worcester Polytechnic Institute,
100 Institute Road,
01609, Worcester, MA, US

Higini Arau – Puchades
Arauacustica,
C/Travessera de Dalt 118,
08024, Barcelona, Spain

ABSTRACT

In recent years a volume diffuser, called grid diffuser or labyrinth diffuser, has been designed and introduced in musical halls. Two examples of this diffuser are described in the present paper: one is the orchestral rehearsal room at the Great Theatre of Liceu in Spain, and other is the Tonhalle St. Gallen hall in Switzerland. In both spaces, musicians and listeners have reported a substantial increase in subjective room volume after the introduction of the diffusers. The initial goal of this diffuser was to reduce the strength of ceiling reflections. However, an increase in the perceived volume occurred unexpectedly. Measurements show that both T and EDT have increased, and also G has been modified by the introduction of the diffusers. Although the lack of a complete theory about labyrinth diffusers, these open new possibilities to obtain the effect of a large enclosure in rooms with relativity lower dimensions, and promise to be important to create smaller and more sustainable halls. Further research is needed to be able to control the mechanism by which the labyrinth diffuser achieves the increase of the reverberation time.

1 INTRODUCTION

This paper describes a new volume diffuser recently designed by one of the author (Arau – Puchades). The challenge of this diffuser is its ability to increase the subjective perception of the volume. Acousticians have been struggling for years with the problem of how to create small and affordable spaces with the reverberation time of large halls. With conventional designs as the room volume becomes smaller, the strength of reflections increases whereas the reverberation decreases. Adding absorption reduces loudness and increases clarity at the expense of reverberation, so that the sound loses richness. Musicians accustomed to performing in larger spaces complain when they perform in small rooms and acousticians respond by making small spaces more and more reverberant. The structure presented in this paper offers an alternative to previous problems, as it makes possible to design an attractive and small space with the acoustic properties of a larger hall.

Diffusers are generally designed and introduced in spaces to scatter an incident wave. The study of the diffraction phenomenon started 350 years ago and was initially formulated by

Huygens in the field of optics. Later Lord Rayleigh addressed the issue in the milestone book "Theory of Sound" [1]. Several other works on the subject were elaborated especially after the studies by Schroeder in the 1970s [2]. Schroeder designed sound diffusers based on maximum length sequences and then on quadratic residue and primitive root sequences, starting a new approach to the design and control of surface scattering [2]. In recent years, researchers such as D'Antonio and Cox have worked on the subject hardly, and have proposed different designs of RPG diffusers, according to ternary and quadriphase sequence diffusers [3,4].

Meanwhile, the study and simulation of scattering in simulation of room acoustics has become more and more important for the prediction of the acoustical properties with calculation. However, also with current software, difficulties occur in the simulation of scattering coefficients which, unfortunately, are often unknown or badly simulated [5,6].

Pogson et al. [7] studied suspending cylinders in front of a Schroeder diffuser as a mean to improve the diffusion. The use of cylinders as part of volumetric diffuser accompanies the interest in cylinder arrays for attenuating sound or reducing transmission at selected frequencies [8]. However, none of the researchers so far has focused on the effect of diffusers on the reverberation time.

In recent years, a volume diffuser, called grid diffuser or labyrinth diffuser, has been designed and introduced in musical halls [9-12]. Two examples of these applications are described in this paper: the orchestral rehearsal room at the Great Theatre Liceu in Spain and the Tonhalle St. Gallen hall in Switzerland. In both spaces, musicians and listeners have reported a substantial increase in subjective room volume after the introduction of the diffusers. The initial goal of these diffusers was to reduce the strength of ceiling reflections. However, the increase in the subjective size of the spaces occurred largely unexpectedly. Measurements showed that both T and EDT increased, and also G was modified by the introduction of the diffusers. Although the lack of a complete theory about labyrinth diffusers, these open a new possibilities for architects to enhance both visual and acoustics properties of musical halls. In fact, the labyrinth diffusers allow us to design the effect of large enclosures in rooms with relativity lower dimensions, and promise to be very important to create smaller and hopefully more sustainable architectures. This papers aims to elucidate the way in which these diffusers work.

2 DESCRIPTION OF LABYRINTH DIFFUSERS

The diffusers discussed in this paper consist of a three-dimensional labyrinth formed by vertically oriented panels, held in place by a steel grid (Figs. 1-2). They are essentially volumetric diffusers [13]. The initial goal of these structures was to reduce the strength of ceiling reflections. This goal was amply accomplished, but an increase of the subjective size of the spaces occurred surprisingly.

It may be obvious that a labyrinth structure increases the effective path length that a sound wave travels before it strikes an absorbing surface. This provokes a delay in the absorption of the sound that may result in longer reverberation. However, this effect contradicts the classical sound diffused theory of Sabine which considers reverberation as independent from the scattering (given the assumption of perfectly diffused sound field). The considered scattering structure combines elements that behave like waveguides with openings and edges where considerable diffraction and diffusion take place. The essential randomness of this process produces a lengthening of sound paths.

The diffusing labyrinth in the orchestral practice room in Liceu is constructed from square polycarbonate panels of 800 mm sides and 10 mm thickness. These are attached to an iron framework (200 mm width and 15 mm thick) suspended from the ceiling (Fig. 1). The panels are transparent, reflective and completely open to the ceiling, so there is little reduction in the subjective height of the room. Diffusers cover all the surface of the room. This has a volume of 1748 m^3 and a floor surface of 278 m^2. A second layer of diffuser of the same design of the first is installed in half of the room. The high reflection of the frame, especially in the part where two layers of diffusers were introduced, provoked a significant increase of low-absorptive area in the room, so that an increase of reverberation time was expected.

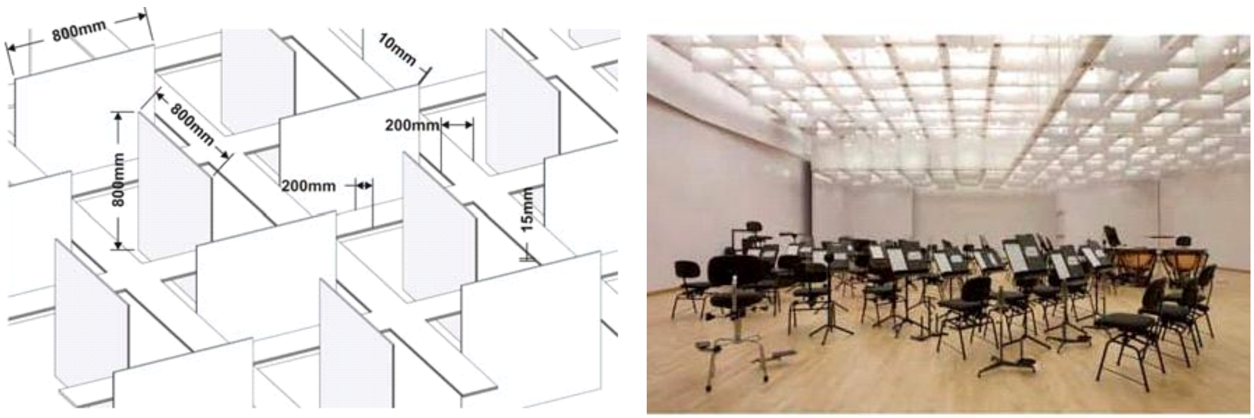

Figure 1: The diffuser design (left) and a photo (right) in the rehearsal orchestra in the Great Theatre Liceu.

The Tonhalle St. Gallen hall in Switzerland is a medium size concert hall built in 1909. It has a volume of 6100 m^3, and an audience surface of 588 m^2 with 840 seats. The position and configuration of diffusers in this hall is shown in fig. 2. In this case, the diffuser is a matrix of gold-laminated plywood plates, supported by a steel grid, like a great lamp. The diffusers cover only the area of the stage. Each diffuser plate is 1000 mm height and 890 mm wide. The entire system is hung by a steel structure. The goal of the design was to eliminate the sound focusing produced by the vault of the room. However, the labyrinth resulted in a significant effect of sound diffusion in the all area.

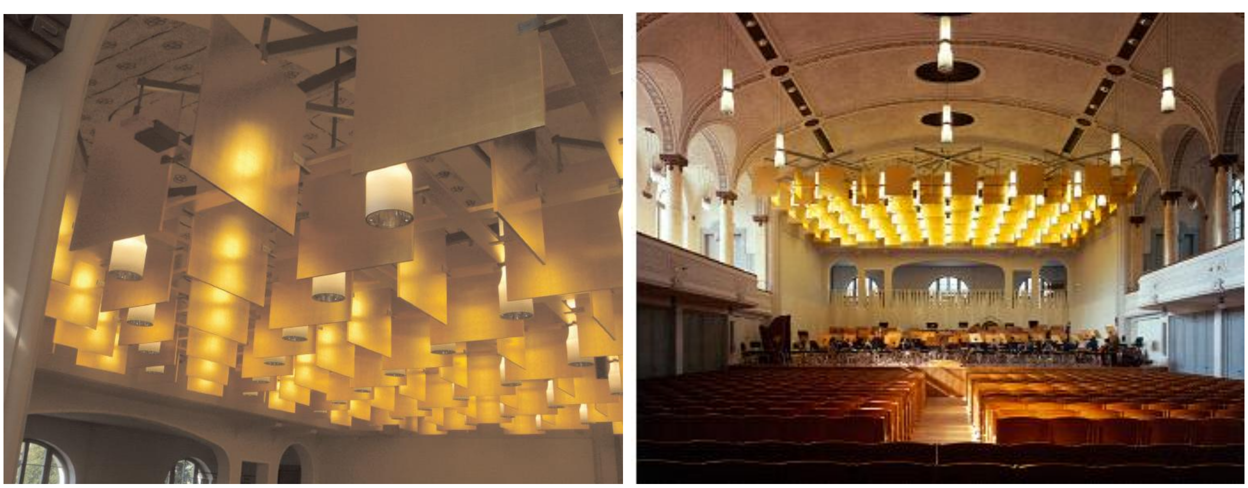

Figure 2: The diffuser design (left) and a photo (right) in the Tonhalle of St. Gallen hall.

2.1 Effects of the Labyrinth Diffusers

In the present section the acoustical effects measured in the two rooms after the introduction of the labyrinth diffuser are described. Standard acoustic measurements were made according to ISO 3382-1. The rooms were measured before and after the introduction of the diffusers. The music stands and chairs were in their usual positions always.

Four source positions and five receiver positions were evaluated in the Great Theatre Liceu. The average results of the reverberation time are shown in Table 1.

Table 1: Reverberation time in the rehearsal orchestra in Great Theatre Liceu, without and with diffusers.

Reverberation Time	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Without diffuser	1.1	1.25	1.10	1.05	1.07	1.03
With diffuser	1.5	1.81	1.92	1.78	1.75	1.67

The stage support parameter value was measured before and after the introduction of the diffuser. This passed from 0.5 dB to -7.3 dB, giving a quantitative proof of the improvement of this room, especially for the musicians.

Standard acoustic measurements were also done in the Tonhalle of St.Gallen. The room was measured before and after the introduction of the diffusers. Average results between 21 receivers in points and 21 receivers on the stage with the sources in four positions on the stage are reported in Table 2, separately for the hall and the stage.

Table 2: Reverberation time in the Tonhalle of St.Gallen hall without and with diffusers, both in the hall and on the stage.

<table>
<tr><th colspan="2">Reverberation Time</th><th>125 Hz</th><th>250 Hz</th><th>500 Hz</th><th>1000 Hz</th><th>2000 Hz</th><th>4000 Hz</th></tr>
<tr><td rowspan="2">Without diffuser</td><td>Hall</td><td>2.47</td><td>2.27</td><td>1.94</td><td>1.90</td><td>1.83</td><td>1.57</td></tr>
<tr><td>Stage</td><td colspan="2">2.16</td><td colspan="2">1.83</td><td colspan="2">1.55</td></tr>
<tr><td rowspan="2">With diffuser</td><td>Hall</td><td>2.42</td><td>2.30</td><td>2.10</td><td>2.06</td><td>1.96</td><td>1.64</td></tr>
<tr><td>Stage</td><td colspan="2">1.93</td><td colspan="2">1.91</td><td colspan="2">1.57</td></tr>
</table>

3 FINDINGS OF THE EFFECT OF THE LABYRINTH DIFFUSER

Looking at the results of the reverberation time in the Liceu, we observed a significant improvement at different frequencies. The increment of T at low frequencies was 0.4 s at middle frequency, and at high frequency was 0.6 s. This shows that the labyrinth diffuser originally installed to reduce the strength of reflections, resulted in many other effects. The increase of the reverberation time was remarkable and the musicians declared that after the introduction of the diffusers they could hear each other significantly better. The authors believe that the large increase of the reverberation time may be attributed to the general reduction of the mean absorption coefficient of the room, which was provoked by the close structure of the diffusers, their low sound absorption, and the presence a rigid horizontal frame frame which covered 1/5 of the ceiling. However, also considering these aspects, the discovery of a device which increases the T of a room is surprising. In particular, this increase contradicts the common knowledge of the reverberation time that considers it proportional to the volume and inversely proportional to the absorption. An effect similar to those obtained in the rehearsal room orchestra of Liceu was reported by Beranek for the Goteborg Konserthus [14]. The authors believe that increase of the reverberation time after the introduction of the diffusers may be attributed to their reflectivity and their open end.

The theory and formula of Sabine do not help to quantify this phenomenon, as neither the volume nor the total absorption have been changed in the room (assuming the diffusers completely reflective). A formula more general of reverberation time has hence been considered:

$$T = (13.9/c) \times l_m / \mathbf{a} = 0.0408 \times l_m / \mathbf{a}, \qquad (1)$$

where l_m is the mean free path of room, (being l_m = 4 V/S), c is the sound velocity, **a** is the average coefficient absorption of the hall, V and S are the air volume and the whole surface of the hall. Thinking the change of T as a consequence of a change of the mean free path, we express the new mean free path of the hall with diffuser as a summation of the original one plus the effect of the diffuser*:*

$$l_{m\_with\ diffuser} = l_{m\_without\ diffuser} + \Delta l_m. \qquad (2)$$

Using equation (1), we have:

$$T_{with\ diffuser} = T_{without\ diffuser} + 0.0408\ \Delta l_m / \mathbf{a}, \qquad (3)$$

This formula may be also re-written in terms of classical Sabine's expression:

$$T_{with\ diffuser} - T_{without\ diffuser} = \Delta T = 0.16\ \Delta V / S\ \mathbf{a} \qquad (4)$$

In our case, at mid frequencies, ΔT is 0.77 s, and being V = 1748 m^3, S = 1018.1 m^2, l_m = 6.87 m, and **a** = 0.256, we obtain that:

$$\Delta V = (0.16 \cdot 0.77) / 1018.1 \cdot 0.256 = 1254.3\ m^3. \qquad (5)$$

The perceived increase of the volume was also confirmed by subjective perception of musicians. For example, the orchestra director Florian Schreiber describing the experience of this room affirmed "It was a small room without a stage and I know how music should sound in such a room normally. But the space acoustically had the sound of a room three to four times larger" [10].

Also the measurements in the Tonhalle St. Gallen Concert showed that the reverberation time increased after the introduction of the diffusers. At middle frequencies the relative increment was 8.3%, whereas at high frequencies, it was 5.9%. At low frequencies a reduction occurred in the values of the reverberation time (-2.0%). The behavior at low frequency may due to the absorption of wood panels which could not be considered transparent to the sound.

The value of the T on the stage shows always higher values with the diffusers: the increment was 6.5% at low frequencies, 9.8% at middle frequencies, and 7.1% at high frequencies.

Using the same methodology reported in formulas (2)-(4), it is possible to affirm that the introduction of the diffusers provoked a perceived increase of the volume between 7 and 10 % depending on the considered frequency.

The EDT particularly increased on the stage, where it resulted 22.4% greater at the middle frequencies, practically the same at low frequencies, and 18% higher at high frequencies.

An important result regarded the analysis of the Gade's criterion of stage support. This parameter did not change significantly after the introduction of the diffusers (it resulted -10.1 and -9.2 dB before and after respectively). However, the real sensation and feedback of musicians on the stage has been particularly different, as they considered the acoustics largely improved. This finding confirms the limits of the Gade's criterion and the need to find better ways to assess the stage support [9].

Finally, an important finding was the change of the strength G: this increased of approximately 1 dB in the hall, whereas decreased by approximately 3 dB on the stage. These results prove a redistribution of the sound energy in the room and a more balanced level of sound on the stage, where problems of focalization under the vault disappeared.

4 DISCUSSION OF THE LABYRINTH DIFFUSERS

The results presented in section 3 show that the labyrinth diffuser can improve the performance of halls by increasing the reverberation time of small rooms. The design arose from an intuition of how sound might interact beneficially with such a structure. This combines the properties of reflection and diffraction in complex ways and being open, it allows sounds to travel in it.

Musicians' comments reveal that the labyrinth diffuser decreases the early reflected energy reaching the musicians [9-10]. This early energy is deflected by the diffuser away from the stage area; reflected sound is forced to travel longer paths before being absorbed and thus the reverberation time is lengthened. It may be easier to think about this process as an increase in path length between the source of a sound and a surface that will absorb it, something that would happen if the volume of the hall increases.

For this scope, it is critical that the labyrinth is open at the end. A sound wave traveling through free space decreases in energy proportional to the square of the distance it travels, whereas a sound wave traveling in a channel or tube does not lose energy as it moves along. Thus to emulate an increased path length effectively the labyrinth design must allow the sound energy to propagate as it travels through the device. This is precisely what the labyrinth design does: it combines parallel surfaces and open spaces, maximizing the opportunity for both reflection and diffraction to occur. Both in Liceu and in St. Gallen the labyrinth diffuser increased the perceived size of the space and the measured reverberation time. In Liceu, where the diffuser covers the entire ceiling of a small space, the increase in space and reverberation time resulted higher, whereas in St Gallen, the effect was less, but still highly appreciated.

The ability of the labyrinth to guide and diffract sound is frequency dependent. The panel size in both cases was about one square meter, implying that sound with a frequency below 1000 Hz was not substantially guided by the structure. This seems to be confirmed by the higher effect at high frequencies.

Both in Liceu and in St. Gallen the early reflections were too strong and came too soon to allow mixing and balancing direct sound and early reflections. Adding the labyrinth diffuser reduced the strength of these reflections and increased the time delay between the direct sound and the reflections. Both the lower energy and the increased delay improved hearing conditions on stage.

A scale model test of the diffuser has been done to measure its scattering coefficient according to ISO 17497-1 [15] at the Universidad Politecnica de Valencia. Fig. 3 reports the test configuration. The scattering resulted particularly high in the frequency bands of 250 Hz (scattering coefficient equals to 0.75), 400 and 630 Hz (0.35) and 1600 Hz (0.43).

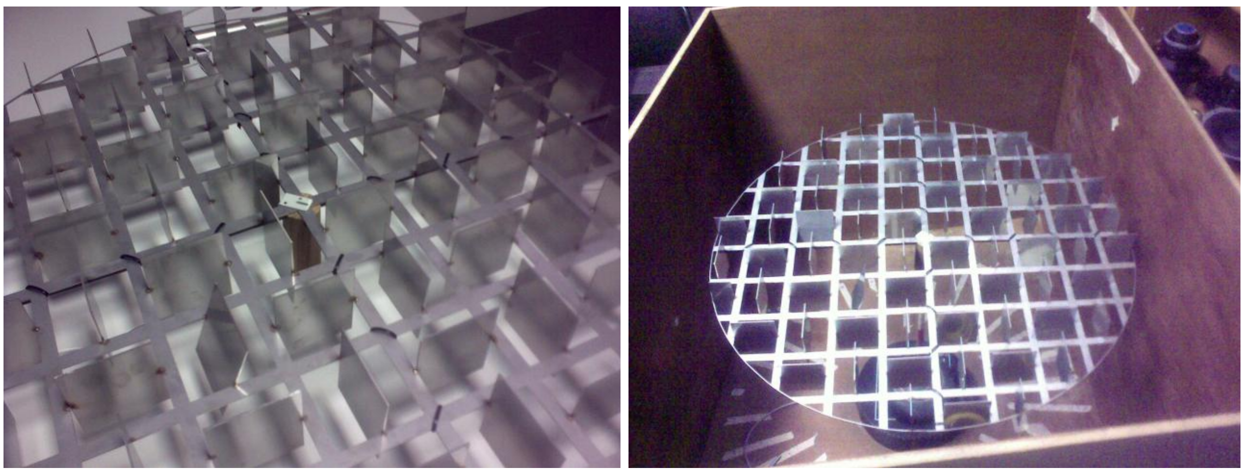

Figure 3: Photos of the scale model for the study of the diffusers [16]

A virtual model of the St.Gallen hall was then realized with CATT-Acoustics to understand the way in which the diffusers behave. The software predicts direct sound and first-order deterministic methods and image source sources and high-order reflections using randomized tail-corrected cone tracing. Higher order reflections are the result of independent ray/cone tracing for each octave-band taking into account the frequency dependence of diffuse reflections selecting randomly specular or diffuse via scattering coefficient magnitude where a diffuse ray is reflected using the Lambert distribution. The simulation algorithm used by this software and description of how scattering is considered can be found in [6].

The virtual model was calibrated with the measured values and the fitting resulted particularly good with deviations from the measured parameters always below 6%. The simulation result confirmed the measurement predictions: the labyrinth diffuser is able to increase the reverberation time also in the virtual model both on the stage and in the hall (Fig. 4). The variation was more significant at higher frequencies than at lower frequency, as we expected. In particular, at 125 Hz, a light reduction (0.2 s maximum) of the reverberation time occurred especially at the end of the hall. Moreover, it was noted a significant increase of the reverberation time in the area of the stage and in the homogeneity of this parameter in any frequency band, with more significant increase at middle and high frequencies.

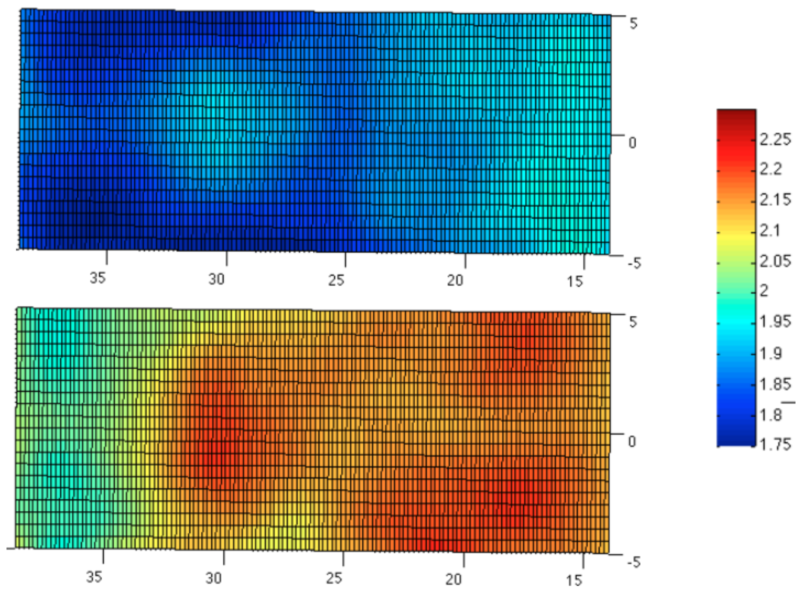

Figure 4: Color map of the reverberation time at 500 Hz on the plan of Tonhalle of St. Gallen hall without (above) and with (below) the diffusers, the origin of the axis is on the symmetric axis behind the stage

5 CONCLUSIONS

This paper has presented the design of a labyrinth diffuser that combines the properties of multiple reflections and edge diffraction in a way to increase the effective path length of diffused sound. The results show increased reverberation, higher clarity, and a considerable improvement of listening conditions. Comments by both musicians and listeners have been particularly positive after the installation of the labyrinth diffusers. People reported that the sound has become more reverberant, and has achieved the spatiality typical of larger spaces. Measurements have confirmed these improvements in the acoustic properties of the rooms. The paper presented a simple way to measure and evaluate the increase of the subjective volume of hall due to the addition of the volumetric diffuser. However, a new mathematical theory is necessary to explain the physical phenomena of labyrinth diffusers. Research is necessary to provide formulas to calculate the additional reverberation as a function of the size the plates, their distance from the floor and the ceiling, and their surface in relation to the ceiling area. Finally, even without such a theory, the labyrinth diffuser opens new possibilities to enhance the acoustical properties of large halls in smaller, more affordable and more sustainable halls.

REFERENCES

1 John William Strutt (Lord Rayleigh), "The theory of Sound", *Macmillan* (1896).

2. Manfred Schroeder, "Diffuser Sound Reflection by Maximum Length Sequences", J. Acoust. Soc. Am., Vol. 57, n. 1, 149-150 (1975).

3. Trevor Cox and Peter D'Antonio, "A brief history of room acoustic diffusers", Acoustics Today, Vol. 2, n. 3, 18-25 (2006).

4. Trevor Cox and Peter D'Antonio, "Acoustic Absorbers and Diffusers: Theory, Design and Application", *Taylor & Francis* (2009).
5. Trevor Cox, B.I. L. Dalenback, P. D'Antonio, J.J. Embrechts, J.Y. Jeon, E. Mommertz, M. Vorlander, "A Tutorial on Scattering and Diffusion Coefficients for Room Acoustic Surfaces", Acta Acustica united Acustica, Vol. 92, n. 1, 1-15 (2006).
6. Umberto Berardi, "Simulation of acoustical parameters in rectangular churches", J. of Building Performance Simulation, vol. 6, n. 3, 2013, http://dx.doi.org/10.1080/19401493.2012.757367
7. M.A. Pogson, D.M. Whittaker, G.A. Gehring, T.J. Cox, R.J. Hughes, and J.A.S. Angus, Diffusive benefits of cylinders in front of a Schroeder diffuser, J. Acoust. Soc. Am., Vol. 128, n. 3, 1149-1154 (2010).
8. Olga Umnova, Keith. Atteborough, Chris Linton, "Effect of porous covering on sound attenuation by periodic arrays of cylinders", J. Acoust. Soc. Am., Vol. 119, n. 1, 278-284 (2006).
9. Higini Arau-Puchades, "An acoustics miracle of "Tonhalle St. Gallen" has been produced. but the criterion of Gade on stage has failed before and after the refurbishment of the hall", Proc. of the Institute of Acoustics, Vol. 33 (2011).
10. Higini Arau-Puchades, "Increasing the Acoustic Volume of Performance Spaces without Altering the Internal Dimensions", Acta Acustica united Acustica, Vol. 98, n. 2, 309-316, (2012).
11. Higini Arau-Puchades, "The Refurbishment of Orchestra of Rehearsal Room of Great Theatre of Liceu", Building Acoustics, Vol. 19, n. 1, 45-56 (2012).
12. Higini Arau-Puchades, "The Refurbishment of Tonhalle St. Gallen", Building Acoustics, Vol. 19, n. 3, 185-204 (2012).
13. Richard James Hughes, "Volume Diffusers For Architectural Acoustics", University of Salford, Salford, UK, PhD Thesis (2011).
14. Leo Beranek, "Concert halls and opera houses. Musics, acoustics and architecture", *Springer Verlag* (2004).
15. ISO/DIS 17497-1 - Measurement of the sound scattering properties of surfaces - Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room. ISO (2001).
16. Alejandro de Frutos Capellán, "Estudio de la colocación de un difusor simétrico en el auditorio "Tonhalle St.Gallen", UPV - Gandia, ES, MSc Thesis, (2012).