No. 2 · pp. 199–364 · March/April 2012 · E 21 466 · ISSN 1610-1928 Volume 98

ACTA ACUSTICA

UNITED WITH

ACUSTICA

The Journal of the European Acoustics Association (EAA) · International Journal on Acoustics

Table of Contents

Review Article

Scientific Papers

No. 2 · pp. 199 – 364 · March/April 2012 · E 21 466 · ISSN 1610-1928 Volume 98

ACTA ACUSTICA
UNITED WITH
ACUSTICA

The Journal of the European Acoustics Association (EAA) · International Journal on Acoustics

S. Hirzel Verlag · Stuttgart

Acta Acustica united with Acustica
Vol. 98 (2012) 309 – 316

DOI 10.3813/AAA.918514

Increasing the Acoustic Volume of Performance Spaces without Altering the Internal Dimensions

Higini Arau-Puchades
Arau Acustica, www.arauacustica.com

Summary
Diffraction phenomenon is 350 years old. It was born with C. Huygens in optics field and also was developed by J. W. S. Rayleigh 1896. During several decades several works were developed by several researchers of International Community, between them M. Schroeder proposed sound diffuser for the first time. After, have arose many papers of scattering directed by P. D'Antonio and T. Cox. Here in this paper we present a novel acoustic labyrinth that increases the effective volume of a performance space without increasing the internal dimensions. Two examples of the device will be described: one in the orchestral rehearsal room at the Liceau Theater (Great Theatre Liceu), and one in the Tonhalle St. Gallen. Both in Liceu and St. Gallen musicians and audience report a substantial increase in subjective room volume and clarity. Conventional acoustic measurements verify these reports. In Liceu, where the labyrinth covers nearly the entire ceiling, the reverberation time (T_{30}) at 500 Hz increased from 1.1 seconds to 1.9 seconds. The musicians find the conditions in the rehearsal room – previously deemed difficult to impossible – optimal and nearly identical to the acoustics of the Gran Theatre. In the Tonhalle St. Gallen the diffuser occupies proportionally less area, but RT, EDT, and G all increased, and the response by musicians, audience, and critics has been overwhelmingly favorable. Further research is needed to elucidate the mechanisms by which the labyrinth achieves these improvements, but the results in these venues suggest that this type of structure has an important role to play in acoustic design, particularly in smaller venues.

PACS no. 43.55.Br, 43.55.Fw, 43.55.Hy

1. Introduction

Diffraction phenomenon is 350 years old. The concept was born with Huygens in the field of optics. Later James Williams Strutt, Lord Rayleigh, addressed the issue in the Theory of Sound [1]. Several works on the subject were elaborated last century by the International Community,between them M. Schroeder proposed sound diffusers for the first time [2]. Later, researchers such as P. D'Antonio and Trevor Cox [3, 4] , prepared a number of scientific communications on the subject, the RPG diffuser. Surface diffusers were well known and measured. Over the last twenty years, significant research on methods to design, predict, measure and quantify RPG sound diffusing has been increased in this area. Application of scattering in PC simulation room calculation made the reverberation time RT to be reduced always when the scattering value of the diffuser is taken into account. This effect is well known by application user, being observed in both cases of our project. But the reality, in both our cases, was quite different when calculated by PC. Meanwhile M. A. Pogson *et al.* [5] studied suspending cylinders in front of a Schroeder diffuser as a means to improve diffuser performance. The use of cylinders as part of volumetric diffuser contrasts with the majority of interest in the acoustic of cylinders arrays, which has concentrated on sound attenuation or reduced transmission at selected frequencies O. Umnova *et al.* [6], J. V. Sanchez-Perez [7]. This effect has also been found in our volumetric diffuser. The aspect of diffraction cylinders have also been studied by G. Dumery [8]. He found that a grid of cylinders, or obstacles, being hit by sound waves creates a diffraction that gives a sound attenuation. None of this research showed the experimental effect of the diffuser suspended above increase of reverberation time. We will discuss this issue later in the part on the designed device.

Now the structures discussed in this report consist of a three-dimensional labyrinth formed from vertically oriented parallel panels approximately one meter square, held in place by a steel grid and suspended from the ceiling. It is essentially a volumetric diffuser. The initial goal of the structure in both venues was to reduce the strength of ceiling reflections, and this goal was amply accomplished. The dramatic increase in the subjective size of the spaces came as a surprise. In retrospect it may seem obvious that a labyrinth structure might increase the effective path length a sound wave needs to travel before it strikes an absorbing surface, but the effect – here demonstrated as real – is difficult to calculate precisely. The structure described in this paper combines elements that behave like waveguides with openings and edges where considerable diffraction

Received 10 May 2011,
accepted 27 November 2011.

and diffusion takes place. The essential randomness of this process appears to produce a lengthening of sound paths, resulting in an increase in reverberation time without an increase in the physical volume of the room.

Musicians, acousticians, and the public have been struggling for years with the problem of how to create a smaller, affordable space with the clarity and reverberation time that a large space delivers. With conventional designs as the room volume becomes smaller the strength of reflections and reverberation increases, and the time delay between the direct sound and the reflected energy decreases. The space becomes loud and muddy. Adding absorption reduces loudness and increases clarity at the expense of late reverberation, and nearly all historic music performance spaces were both small and absorptive. But absorption decreases the reverberation time, and the sound loses the richness that just the right amount of reverberation can provide. Musicians accustomed to performing in larger spaces complain when they perform in small rooms. Architects and acousticians respond by making small spaces more and more reverberant, decreasing clarity both on stage and to the public. The structure presented in this paper offers an alternative. It makes it possible to design an attractive and affordable space with the acoustic properties of a larger hall, and offers a cost-effective method of improving conditions in existing halls and rooms.

2. The labyrinth diffuser installed in an orchestral rehearsal room in the Gran Theatre Liceu

2.1. Introduction case 1

The Orchestral Rehearsal Room in the Gran Theatre Liceu was inaugurated in October of 1999 along with the new Grand Theater. The rehearsal room was adequate for a medium-sized orchestra, but with a large orchestra the sound was too loud, too dry, and the musicians were unable to hear each other properly. It was not possible to increase the size of the space, as the urban planning authorities in Barcelona had put limitations on the size of workspaces, rehearsal rooms and other spaces in the theatre complex. The labyrinth diffuser was invented and installed in an effort to reduce the strength of reflections from the ceiling. The result was remarkable. Not only were the musicians able to hear each other, the reverberation time increased almost to the value that existed in the main theater [9].

The proposal by Arau Acustica was delivered to the owner of the Liceu in July of 2007, and the refurbishment work was carried out in August. The civil concept, the planning and the execution control of the building works were carried out by Dilmé–Fabré Architects, Barcelona, with collaboration from the acoustic consultancy firm of Arau Acustica. The volume of the space was marginally increased from 1433 m^3 to 1748 m^3 by removing a lowered ceiling. Acoustic measurements, were made in the space before and after the volume were increased, and then after the labyrinth diffuser was installed.

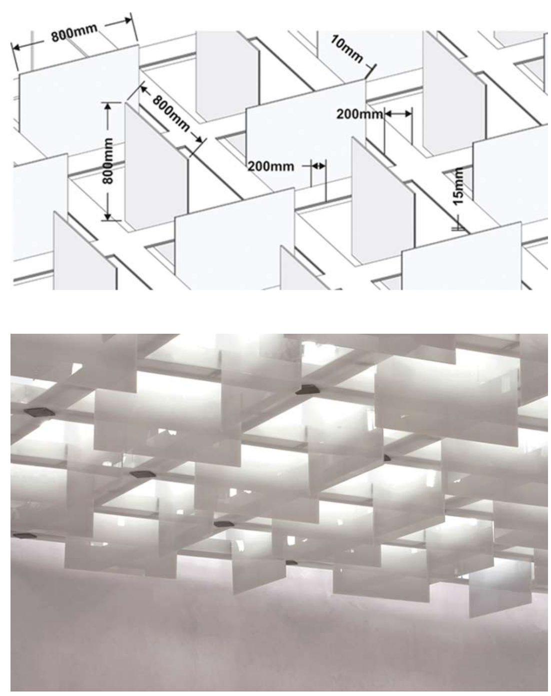

Figure 1. The diffuser in the rehearsal orchestra in Liceu.

2.2. The diffuser design

The diffusing labyrinth in the orchestral practice room in Liceu is constructed from square polycarbonate panels 800 mm on a side. These are attached to an iron framework suspended from the ceiling. An additional diffuser of the same design is installed on top of the lower one in the part of the room where the ceiling is the lowest. The panels are transparent polycarbonate and completely open to the ceiling, so there is little reduction in the subjective height of the room.

Unlike conventional diffusing surfaces which simply scatter or defocus sound, the new structure guides sound through a myriad of tunnels formed by parallel panels. These tunnels are not continuous. Sound diffracts from the edges of each panel, taking a complex and varied path through the structure. It would seem that sound traveling vertically would not be affected by the structure, but the ceiling in Liceu is peaked, and the ceiling in St. Gallen is curved, so sound traveling vertically up through the structure is deflected obliquely down on its return path. The net result is an increase in the time delay and a reduction in sound strength before the sound strikes an absorbing surface – just as if the distance to the absorbing surface had increased.

2.3. Subjective perceptions of Swiss musicians to the labyrinth diffuser in Liceu

The diffuser in Liceu is startlingly effective – and the way it works is so novel that it must be heard to be believed.

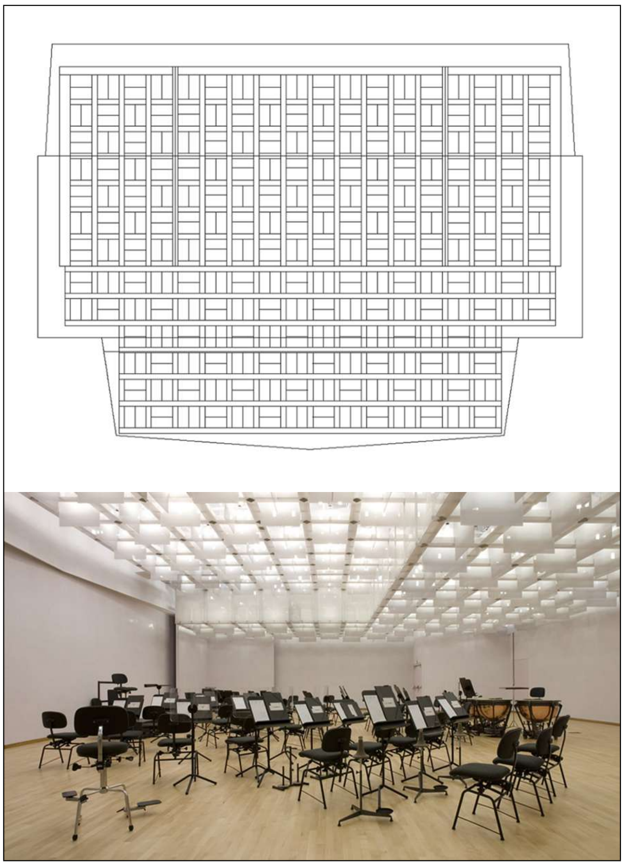

Figure 2. Plan and photo of the labyrinth diffuser in the Liceu rehearsal room.

Because the problems in St. Gallen [10] also involved poor stage conditions Higini Arau believed that a similar labyrinth diffuser would be effective there. Two musicians from Switzerland traveled to Barcelona to experience the practice room in Liceu, and their impressions are described in the newspaper article below:

> From: Regionkultur: 14. Juli 2010, 01:04, Tafel-Himmel für den Wohlklang, Andreas Stock
>
> TRANSLATION German to English:
>
> Surely an effect that is so easy to hear should be possible to calculate. But in the opinion of the concert director "a symphony orchestra is the most demanding and complex source of sound." The St. Gallen building director opined that sound from such an demanding source "is a natural phenomenon that is unbelievably difficult to explain." Six weeks were spent with computer modeling to determine the how the diffusing panels should be arranged. But the calculations could only go so far. The total impression and the effectiveness of the sound can only be heard in the hall, and this is the only way to appreciate how well diffuser works in practice. The author presented a practice room in Barcelona which had been remodeled using a diffuser of a similar design, and two musicians went to Barcelona to hear it. "It took your breath away", wrote Florian Scheiber of the listening experience. "It was a small room with no stage, and I know how music must sound in such a room. But this room worked as if it were three times larger."

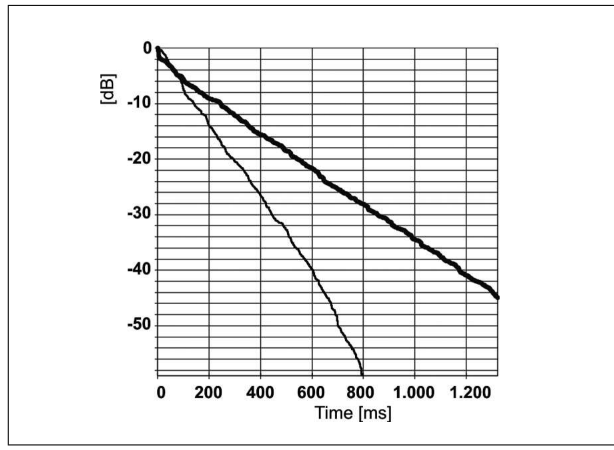

Figure 3. A typical 500 Hz Schroeder decay curve in the Liceu rehearsal room. The thick line is after refurnishment, the fine line before refurnishment.

2.4. Measurement methodology and results

Standard acoustic measurements were made in Liceu using the methods of ISO 3382-1, [11, 12]. The room was measured in its original state (case 1), after the volume was increased (case 2), and after the diffuser was installed (case 3). The music stands and chairs were in their usual positions for all conditions. Four source positions and five receiver positions were averaged to obtain the data shown in Table I.

Adding the diffuser, results in a very significant increase in the reverberation time, especially at 500Hz and above. Unfortunately it was not possible to measure G in these measurement sessions – but subjectively the loudness of the room did not increase. The sound decay with the diffuser in place is linear, just as if the room volume had increased without any change in the total absorption. The EDT values also increased when the diffuser was added.

3. The labyrinth diffuser installed in the Tonhalle St. Gallen

3.1. Introduction case 2

The Centennial St. Gallen Concert Hall in Switzerland [10] is used as a concert hall, but its size is more characteristic of a chamber hall. The hall was inaugurated in 1909, but there have always been many issues relating to the stage, such as high levels of sound, focusing, and flutter echoes. These problems were never solved. The Director of the Orchestra and his musicians were generally very unhappy with this hall, as musicians had a lot of trouble hearing each other, and the flutter echoes were very strong. A restoration project in 1992-1993 lengthened the room and updated the seating. But this renovation did not affect the problems on stage. In 2009, 100 years after the

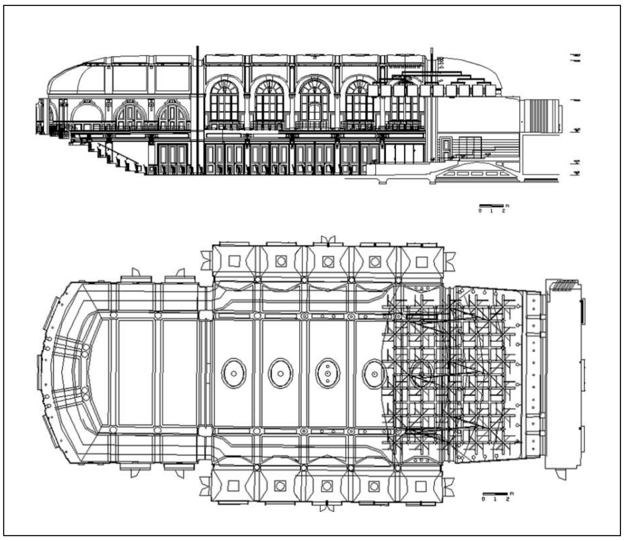

Figure 4. Long section and overhead of the hall after refurbishment in 2010.

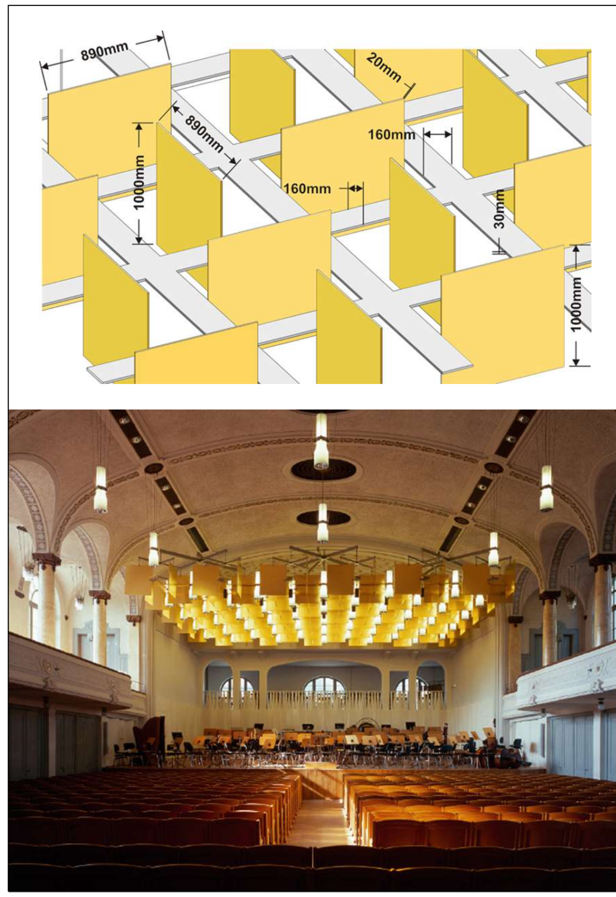

Figure 5. The labyrinth diffuser as seen from the rear of the hall.

inauguration, an international tender was issued to refurbish the hall. The planning and the execution of the building works were carried out by Bosshard Vaquer Architects, Zurich, with acoustic consultancy provided by Arau Acustica, Barcelona. The most significant change during this project was the addition of the labyrinth diffuser, although the stage floor and stage walls were also refurbished, the latter being fitted with plywood panels on an incline to avoid flutter echoes.

3.2. Hall geometry before and after the renovation in 2010

The 2010 renovation changed some of the stage profiles, but did not change the volume of the hall or the position or number of the audience seating. The basic hall data is shown here:

Geometry Air volume	$6100\,m^3$
Audience capacity	840 seats
Audience surface	$S_A = 588\,m^2$
Volume by seat	$V/N = 7.32\,m^3$/seat
Volume by audience area	$V/S_A = 10.459\,m$

Architectural details:
The walls beneath the balcony are wood paneling, and the under balcony soffit is also wood. The other walls and decorations are plaster, as are the balcony fronts. Ceiling is plaster, floors are wood parquet. The stage floor is oak over an air space. Stage height is 95 cm above the first-seat floor level. Seats are upholstered wood.

The position and general configuration of the labyrinth diffuser can be seen in the Figures 4, 5. The diffuser is a matrix of gold-laminated plywood plates, supported by a grid of steel squares. Each diffuser plate measures 1000 mm height × 890 mm wide. The entire system is hung by a steel structure from 3 points in ceiling, like a great lamp. The goal of the design was to eliminate the sound focusing produced by the curvature between the ceiling and walls in the hall. It was expected that the labyrinth would reduce these reflections by scattering sound in all directions, and this goal was achieved. The resulting diffuser works acoustically much better than expected. Although such a diffuser design has never been used before in a concert hall, the people of the City of St. Gallen consider it to be a brilliant and very beautiful solution. The reform has received the top architectural prize 2005–2010 of Switzerland.

The primary unexpected advantage of the labyrinth diffuser is that it increases both the apparent subjectively size of the stage area and really increased rather than decreased the reverberation time in frequency. In low frequency the RT is decreased by membrane absorption of wood plates compensating so the increasing produced by diffuser. At least one previous case is known in scientifically literature. This diffuser of a different design installed by Niels Jordan in the Goteborg Konserthaus [13] to see Figure 6, was also found to increase the reverberation time and the early decay time of the hall.

3.3. Measurement methodology and results

Standard acoustic measurements were made in St Gallen using the methods of ISO 3382-1, [11, 12]. The methodology was similar to that used in Liceu, but in addition to RT, and EDT, the hall gain, G, and the stage support ST1, were also measured both before and after the installation of the labyrinth diffuser [10]. As in Liceu the diffuser significantly increased both RT and EDT in the hall. The

Table I. Reverberation time as a function of frequency for three conditions of the room. Case 1: before modification, Case 2: after the volume of the room was somewhat increased. Case 3: after the diffuser was installed.

Reverberation time T (s)	125	250	500	1000	2000	4000	RT_{mid}	RT_{low}	RT_{high}
$T_{30CASE1)}$	0.9	1.03	0.89	0.86	0.86	0.85	0.87	0.97	0.85
$T_{30CASE2)}$	1.1	1.25	1.10	1.05	1.07	1.03	1.07	1.17	1.05
$T_{30CASE3)}$	1.5	1.81	1.92	1.78	1.75	1.67	1.85	1.67	1.71
$\Delta T_{21} = T_{30case2)} - T_{30case1)}$	0.19	0.22	0.21	0.19	0.21	0.18	0.20	0.20	0.20
$\Delta T_{32} = T_{30case3)} - T_{30case2)}$	0.43	0.56	0.82	0.73	0.68	0.64	0.77	0.50	0.66
$\Delta T_{31} = T_{30case3)} - T_{30case1)}$	0.62	0.78	1.03	0.92	0.89	0.82	0.97	0.70	0.86

Table II. Average reverberation time T_{30} before and after the modifications in 2010. The values of EDT are similar to the RT values shown here.

Frequency	125	250	500	1000	2000	4000	RT_{mid}	RT_{low}	RT_{high}
T_{30} (s) 2009	2.47	2.27	1.94	1.90	1.83	1.57	1.92	2.37	1.70
T_{30} (s) 2010	2.42	2.30	2.10	2.06	1.96	1.64	2.08	2.36	1.80
$\Delta T_{30} = T_{30,2010} - T_{30,2009}$	−0.05	0.03	0.16	0.16	0.13	0.07	0.16	−0.01	0.10

Table III. G values in the audience area before and after renovation in St. Gallen.

Frequency	125	250	500	1000	2000	4000	G_{mid}
Strength G_{2009} (dB)	10.8	8.2	7.8	8.2	9.3	7.3	8.00
Strength G_{2010} (dB)	9.5	9.4	9.2	9.1	10.0	8.9	9.15
$\Delta G = G_{2010} - G_{2009}$ (dB)	−1.3	1.2	1.4	0.9	0.7	1.6	1.15

Table IV. Average of G values measured on stage as a function of frequency before and after renovation.

Frequency	125	250	500	1000	2000	4000	G_{mid}
Strength G_{2009} (dB)	11.0	8.4	8.0	8.6	9.6	7.6	8.9
Strength G_{2010} (dB)	5.7	7.0	6.0	5.6	6.3	4.6	5.8
$\Delta G = G_{2010} - G_{2009}$ (dB)	−5.3	−1.4	−2.0	−3.6	−3.3	−3.0	−3.1

Figure 6. Nils Jordan's diffuser in Gotenborg Koncerthaus.

diffuser was also highly effective in reducing the focused reflections on stage, which decreased the excessive loudness and improved clarity. The new stage conditions were judged far more satisfactory by the musicians, even though the measured values of ST1 before modification are similar to the recommendations of Gade, and the new values are below the recommendations. The points of measurement are given in [10].

Figure 8 shows the value of G in the audience area decreasing with distance. The slope of the decrease is quite close to the value predicted by Barron's revised theory [14]. The value of G – and thus the strength of the orchestra in the audience area – significantly increased when the labyrinth diffuser was added. A possible explanation for this increase can be inferred from measurements of G on the stage.

Mitigating the focused reflections that bombarded the stage was one of the main goals of the renovation, and the data in Table IV shows that the diffuser substantially reduced the excess sound strength. Listening conditions on stage were greatly improved. More experimental are given in [10].

It is not obvious from classical acoustics why the value of G in the hall should increase while the value of G on stage decreases. But there is a simple explanation. The stage area when occupied with stands and chairs is somewhat sound absorptive, and is very absorptive when fully occupied by musicians. The excess energy we see on stage before the renovation would be nearly completely absorbed under occupied conditions. This energy is then unavailable to the audience. The labyrinth diffuser does

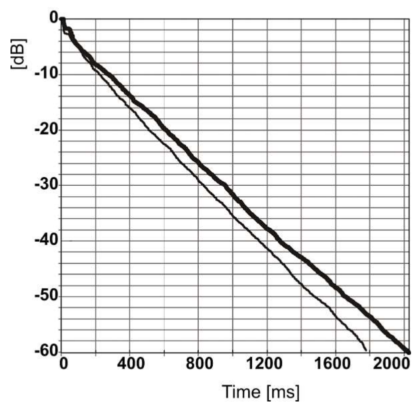

Figure 7. Normalized 1 kHz octave band Schroeder decay curve in St. Gallen, source position F1 to receiver 3. Thick line is after refurnishment and fine line is before refurnishment. Note that the increase in reverberation time is significant and the decay is linear.

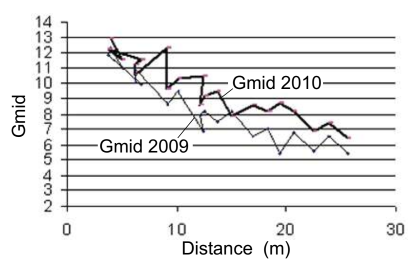

Figure 8. Gmid in the audience area as a function of distance in 2009 (fine line) and after renovation (thick line).

not absorb this energy, but re-directs it into the audience area. Thus we expect that a decrease in G on stage will result in an increase in G in the audience area. The data show that this transfer of energy takes place, and can be measured even in the unoccupied hall. Comments from audience and musicians confirm that the transfer also takes place – probably to a greater degree – when the hall is occupied.

4. Discussion of the results in Liceu and St. Gallen

The results presented above show that the novel labyrinth diffuser can be a powerful tool in improving the performance of existing rooms and halls, particularly when space and cost are limited. The design shown here arose from an intuitive understanding of how sound might interact beneficially with such a structure. The designs succeed beyond all expectations. The reasons for such success are not entirely clear. This type of structure combines the properties of reflection and diffraction in complex ways. In reality the future will need to find a new physical theory that explains the phenomena produced by these volumetric diffusers.

In our project we studied the problem as an approximation for ray tracing, with several software of room simulation. The results calculated went well different to reality obtained by measurements. Maybe, we think that further research – most likely with scale models – may reveal even more successful designs based on the same principles.

But applying some of the same intuition that went into the original design can perhaps clarify at least a few of the reasons we obtain the results we see and hear. An explanation for the increase in G in the hall – a highly desirable result – is suggested in the section above.

The result seems contrary to the predictions of classical acoustics, and it is. The problem is with the simplifications that were made in deriving the classical acoustic equations and not with the measurements in the hall or the perceptions of the people who listen and play there. Classical acoustics predicts that the value of G should depend only on the total absorption in the hall. In these two cases the absorption in the hall did not change, and consequently classical acoustics would predict that G would not change. But the classical acoustic equations are based on the concept of a classical mean free path a concept that makes sense only if the surfaces of the space have uniform absorption. And this is almost never the case in performance halls. Classical acoustics also makes the assumption that the strength of the reverberation is uniform throughout the room, an assumption that is approximately correct in reverberation chambers, but in larger spaces is false mathematically, a result that has been confirmed by the revised theory of Barron.

Mathematically we would expect the strength of the reverberation in a space with uniform absorption to decrease with distance at a rate equal to the decrease predicted from the reverberation time as the reverberant sound travels from the source to a receiver. For a space with a reverberation time of two seconds, this works out to be about 1 dB for every 10 meters of distance from the source. The reverberation time is somewhat shorter in St. Gallen – and so in St. Gallen the rate of decrease should be somewhat greater. The rate of decrease shown in Figure 8 is almost exactly what we would expect, even though the Tonhalle St. Gallen does not have uniform absorption on all surfaces.

The fact that reverberant strength is not the same throughout the hall is important, because it means that sound absorption close to the source of sound will have a greater effect on the total value of G. Where the reverberant or reflected level is strongest absorption is more effective than in areas where the reflected and reverberant energy is weak. By reducing the sound strength and thus the sound absorption in the stage area, the labyrinth diffuser increases the value of G in the audience area.

Musicians comments reveal that the labyrinth diffuser in Liceu also decreases the early reflected energy coming down onto the musicians. This early energy is deflected by the diffuser away from the floor, but it is not absorbed. Reflected sound is forced to bounce around for a while before finding an absorptive surface, 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 hall volume was increased. This is precisely what we hear subjectively.

It is critical that the labyrinth is not composed of closed channels. A sound wave traveling through free space decreases in energy proportional to the square of the distance it travels. But 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 for the sound energy to spread out as it travels through the device. This is precisely what the design presented here 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 increases the perceived size of the space and increases the measured reverberation time. In Liceu, where the diffuser covers the entire ceiling of a small space, the increase in space and reverberation time is dramatic. The effect in St Gallen is less – but is still highly appreciated.

The ability of the labyrinth to guide and diffract sound is frequency dependent. The panel size in both cases is about one meter square – implying that sound with a frequency below 300 Hz will not be substantially guided by the structure. In fact, we see in table 2 that the reverberation time in St. Gallen at 125 Hz decreased slightly when the diffuser was installed, the membrane absorption of wood plates it increased the effect of absorption. At 250 Hz and above, the reverberation time increases significantly. At frequencies above 1000 Hz it may be possible to model some of the characteristics of the structure with ray tracing, as the panels are large enough to create specular reflections. But above 2000 Hz the structure may start to act as a waveguide – with insufficient spreading of sound. We see in Table II that at higher frequencies there is less increase in RT due to the diffuser. It may be possible to design a similar structure that is more independent of frequency. But the frequency dependence we see in both Liceu and St. Gallen is not serious, and may even be desirable. The intuition to make the structure open and the panels about one meter square has been amply justified.

Recent work in the physiology and neurology [15] of hearing points out that problems of hearing on stages and in rehearsal rooms is often due to an excess of early reflection, and not to their lack. The critical issue in hearing other musicians on stage is the musician's ability to separate their own sounds from the sound of other musicians. This is an example of the well-known cocktail party effect. Strong early reflections inhibit our ability to perform this separation. Both in Liceu and in St. Gallen the early reflections were too strong and came too soon to allow the cocktail party effect to work. 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 allowed the brain time to perform the cocktail party effect, and hearing conditions on stage improved. In St. Gallen before the modification in 2009 curved surfaces above the stage also focused some of the sound into the audience. It is possible that reducing the strength and increasing the time delay of these reflections through the addition of the labyrinth diffuser also increased clarity in the audience area.

5. Conclusions

This paper has presented the design of a novel labyrinth structure that is capable of greatly improving listening conditions in small spaces. The structure combines the properties of multiple reflections and edge diffraction in such a way as to increase the effective path length of randomly diffused sound. The result is greater clarity and increased reverberance at the same time – a holy grail of hall design.

We need a new mathematical theory, which does not exist today, to explain the physical phenomena found. A theory for calculating what size the plates and thickness diffusers should be, the distance they should be from the floor and the ceiling, the surface they should have in relation to the ceiling area, so that the designed diffuser provides us with N (s) of additional reverberation to the reverberation time of the room T_0: $T = T_0 + N$ (s).

Comments by both performers and audience in the two spaces where the structure has been installed have been exceedingly enthusiastic. They typically report that the sound has become both more open and more reverberant – properties of larger spaces that have been previously impossible to achieve in smaller halls. Measurements made in the two locations where the structure has been installed confirm these significant improvements in the acoustic properties of the rooms. However in paper [10] was emitted a simple theory to evaluate increase subjective volume of hall due increment of reverberation by volumetric diffuser.

Although the two examples of the labyrinth presented here have an unusual shape, they are both functional and beautiful. Further research – probably with scale modeling – is needed to determine exactly how these structures work, and how their principles could be incorporated into new forms and designs. But potentially the concept of a labyrinth diffuser will open a new avenue for artists and architects to enhance both the visual and acoustic properties of large and small halls.

Acknowledgement

The experiences described in this manuscript would not have been possible without the participation, encouragement and support of my friend Dr. David Griesinger. I thank very much your personal contribution.

References

[1] J. W. Strutt (Lord Rayleigh): The theory of sound. Vol II. p.89.

[2] M. Schroeder: Diffuse sound reflection by maximum length sequences. J. Acoust Soc. Am. **57** (1975) 149–150.

[3] P. D'Antonio, T. Cox. www.rpginc.com/news/biblio.htm, 1984 to 2009.

[4] P. D'Antonio, T. Cox. www.rpginc.com/news/biblio.htm, 1984 to 2009.

[5] M. A. Pogson et al.: Diffusive. benefits of cylinders in front of a Schroeder diffuser **J. Acoust Soc. Am.** (128) 2010.

[6] O. Umnova, K. Attenborough, C. M. Linton: Effect of porous covering on sound attenuation by periodic arrays of cylinders. J. Acoust Soc. Am. **119** (2006) 278–284.

[7] J. V. Sanchez-Perez et al.: Sound attenuation by a two dimensional array of rigid cylinders. Phys. Rev. Lett. **80** (1998) 5325–5328.

[8] G. Dumery: Sur la diffraction des ondes sonores par des grilles on des resaux d'obstacles. Acustica (1967) 334–341.

[9] H. Arau-Puchades: An orchestral rehearsal room in the great Liceu Theatre: A new phenomenon in 3D-grid diffuser. 42nd Congress Tecniacustica, European Symposium on environmental acoustics and on buildings acoustically sustanaible, Caceres, Spain, 2011.

[10] H. 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. Proceedings of the Institute of Acoustics, **33**, Dublin, 2011.

[11] Standard ISO 3382-1: Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces. International Organization for Standarization, Genève, 2009.

[12] M. Barron: Using the standard on objective measures for concert auditoria, ISO 3382, to give reliable results. Acoust. Sci. Technol. **26** (2005) 162–169.

[13] L. L. Beranek: Concert halls and opera houses. Musics, acoustics and architecture. 2nd edition, Springer Verlag.

[14] M.-L. L. J. Barron: Energy relations in concert auditorium. I. J. Acoust. Soc. **84** (1988).

[15] D. Griesinger: The psycoacustic of apparent source width, spaciousness and envelopment in performance spaces. Acustica united with Acta Acustica **83** (1997) 721–731.