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Sound is a wave.
A new concept of Huygens acoustics diffuser

Higini Arau-Puchades[a]

[a] Arau Acústica, Spain, info@arauacustica.com

Abstract

We know that the reference rooms have diffraction to some extent which has always believed to be good, because the diffuse energy delivered is weaker than a mirror sound energy produced above a smooth wall. So in our case we will explain the importance of the diffraction effects to produce more and better diffusion of sound. Here we will formulate the existing essential difference between the diffraction effect of Huygens and scattering effect of Schroeder. We will distinguish between Huygens diffraction plates versus scattering plates defined by M.R. Schroeder. In our defense of Huygens diffraction we have many cases where we have put to an experimental test, the principle of Christian Huygens. Based on these experiences we can conclude: Sound is a wave and is not a sound ray, and this has become clear in our various acoustic experiments conducted by us. We have proved that the solution of the acoustics of many halls analyzed by us had been treated thinking that the sound are waves, but not rays. Therefore, our opinion is that in future must be required to solve many acoustic problems in halls using mathematical and geometrical methods treating with sound waves. Because it, with the raytracing method is not possible to solve these problems; nor with using the scattering factors, due to this system only is valid in a limited frequency range.

Keywords: acoustic diffuser

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1 Introduction

Diffraction is when waves radiating from a source meet an obstacle; then the wave pattern becomes modified. Normally the approximation of diffraction theory is very complex. It has only been possible to solve some theoretical problems with the theory of Helmholtz's equation [1]. There are only two types of diffraction which are: 1. The cases derived from Huygens' principle, [2]; 2. The cases defined by the laws of scattering discovered by M.R. Schroeder and others, [3].

The main purpose of the diffusing elements is certainly to reduce the speculary reflected energy in amount required. However, nobody knows how much energy must be reducing to obtain a good audition in a Concert Hall.

2 The Huygens' principle behavior

The Huygens' Principle says, [2]: Every point on a wave front acts as a point source; the new wave front is developed tangent to all the wavelets. Diffraction can be understood to phenomenological level using Huygens ' Principle, whereby a wave front can be visualized as a series of point sources, which refer to waves oscillating in response to it and thus contribute to its spread. Although each individual oscillator generates a spherical wave, the interference of all results in a wave travelling in the same direction as the initial wave. This is the true representation of sound, born from the propagation of vibration of particles in the air.
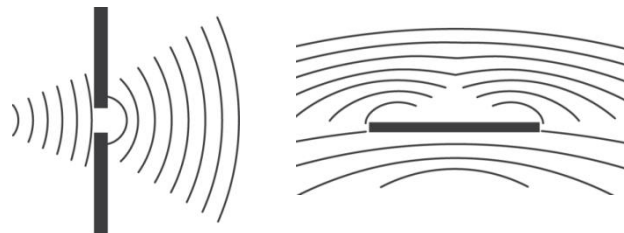

Figure 1: Representative models of Huygens Principle

The Huygens diffusers continuously appear in our daily life. These are planes that are part of our everyday life and appear in the same nature in architecture and also in images represented in sculpturing and painting. We can say that there are so many of these diffusers, Huygens type, that we have not seen because there are many in ordinary life.

The technical implementation of the diffusers in the field of acoustics, with the desire and the need to experience the consequences of Huygens' Principle, was initiated by us in various concert halls which this paper shows.

Ever in our job, we have chosen the frequency range where sound must be diffracted. Recall that frequency and wavelength are related through the speed of sound $c = \lambda f$.

Case 1 derived from Huygens' Principle: If the sound wavelength λ is very small compared to the smallest dimension $L_{x,y}$, of the obstacle and/or air holes w among plate/s, it produces a shadow, and the intensity of radiation at any point is determined by geometrical acoustics. Here it may be useful to work with the system of ray tracing simulation rooms where the laws of reflection obey the laws of mirrors. The dimension of plate, or holes between plates, must be at least:
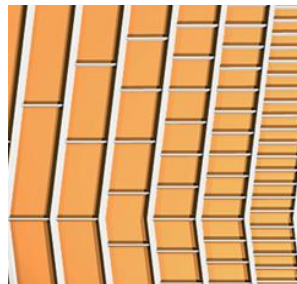
$$1.2 \, L_{x,y} \geq \lambda \tag{1}$$

Case 2 derived from Huygens' Principle: In this case the wavelength λ of sound is approximately equal to the dimension of the obstacle plate (width and long L_x, L_y) or holes size w between plates:

$$0.9 \, L_{x,y} \leq \lambda \leq 1.1 \, L_{x,y} \tag{2}$$

There are two types of diffusers: surface, volume. Each one has different acoustic properties.

a)

Auditorium Barcelona [5]   Pilharmonic Szczecin [6]

b)

Tonhalle St. Gallen [3][11][12][13]   Rehearsal Orchestra room
Great Theatre Liceu, Barcelona [4]

Figure 2: Representative types of Huygens diffusers. a) Surface. b) Volume

Cases 1 and 2 have another big problem which is that they are difficult to design because a lot of imagination is required. And the last problem is that the modern software for room simulation is unable to analyze them. A very important advantage with this diffraction method is that we can play with the sound diffusion, getting almost a perfect sound diffusion in 3D direction.

3 Scattering by wall irregulareties, Qrd., Quadratic-residue diffusor

The diffracted waves radiating from an obstacle which size is smaller than the incident wavelength λ, or $w < \lambda$ for wells or holes, exhibits wide angular distribution, and the process is aptly described as scattering, [1].

Case 3 only for Scattering phenomenon:

$$L_{x,y}(\text{or } w) < \lambda \tag{3}$$

Any irregular coffers, bumps, wood ribbons, metal slats separated with air parallel gap or other designs like a "Periodically uneven surfaces of rectangular profile", if these are very small compared to the wavelength λ of sound , they do not disturb the wall' mirror reflection. The birth of modern QRD diffusers was marked by Manfred R. Schroeders' invention of number-theoretic diffusers in the 1970's. A main irregular wall was developed by M. Schroeder with a diffuser called Quadratic-Residue Diffuser. He solved the problem of a highly diffusing ceiling to reflect most of the sound energy to the side walls so that it would arrive at the listener from a suitable direction for minimizing the IACC. The theory is based on the pseudo-random sequences, for example, the quadratic-residue sequences of an elementary number theory originally investigated by Legendre and Gauss.
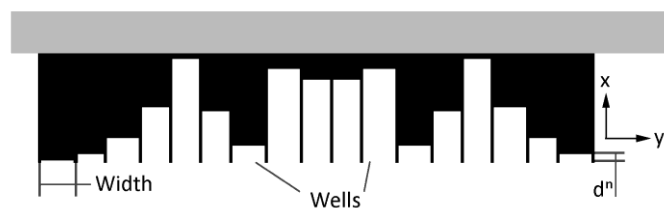
Figure 3: A reflection phase grating based in Quadratic-Residue Diffuser 1 period.

The impedance at each well "w" is expressed by $Z(x;\omega) = -j\dfrac{\rho c}{\tan\left(2\pi\frac{d(x)}{\lambda}\right)}$, where $d_n = d(x)$ is the depth of each well. After algebraic operations we obtain:

$$R_r = \frac{I}{N} w \int_0^{Nw} exp\left(\left[-j\,4\pi\,\frac{d(x)}{\lambda}\right] - j\,2\pi\,r\,\frac{x}{Nw}\right) dx \tag{4}$$

The problem is to design the depth *d(x)* for high diffusion. A good choice is based on the quadratic – residue sequence for *d(x)*, but there are other procedures. The design procedure of the optimum diffuser at θ=0 is as follows:

1. First we must to decide the diffusing frequency range f_{low} and f_{high}, then the minimum period N is approximately given by f_{high} / f_{low}, and also the width w of each well should not exceed c /2 f_{high}. The cross section of this diffuser, with a period N, see figure 3, w (<<λ) being a width of each "well". The problem is to determine the depth $d_n = d(x)$, defined by $d_n = (\lambda/2N)$, where $s_n = n^2$, (n^2 is taken as the least nonnegative remainder module N, and N is an odd prime).

2. From the next equation (4), we calculated the depth of each well d_n is given by

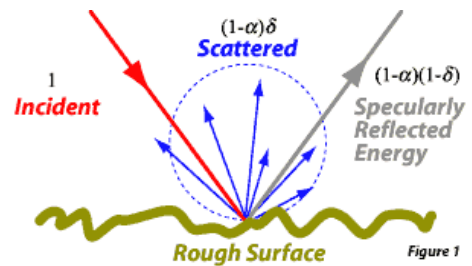$$d_n = (\lambda_d/2N)\, s_v \tag{5}$$

where λ_d is called the design wavelength: ($\lambda_d = c / f_{low}$). The length of period l = Nw.

The reflection of these diffusers, compared to a reflective surface, which will cause most of the energy to be reflected off at an angle equal to the angle of incidence.
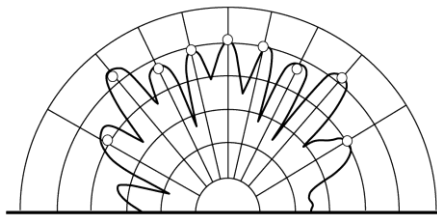
**Figure 4: a) Scattering pattern based on QRD   b) Scattering on any irregularity.**

A diffuser will cause the sound energy to be radiated in many directions, hence leading to a more diffusive acoustic space. It is also important that a diffuser spreads reflections in time as well as spatially. Other types of diffusers of the same family are, MLS and others. Developed by Peter D'Antonio and T. Cox. diffusers can aid sound diffusion, but this is not why they are used in many cases; they are more often used to remove coloration and echoes.

Diffusers are usually used to treat sound aberrations in rooms such as echoes. They are an excellent alternative or complement to sound absorption because they do not remove sound

energy, but can be used to effectively reduce distinct echoes and reflections while still leaving a live sounding space.

We have observed that this angular dispersion of sound is good in small rooms because the sound loss in each direction has a similar behavior to absorption. However, in great halls it is not advisable to use. This phenomenon is known by the manufacturers of software of acoustics simulation. They are using a new magnitude called scattering to adjust the calculations to a better result. In concept, the scattering diffuser is very different to Huygens diffuser. Each one of the two types of diffuser is working in a different manner in relation to the size and the wavelength of sound. However when reflections type Huygens diffusers are produced, the scattering concept used in software simulation must not be applied here, because it is not true. Therefore the scattering diffuser is very different to the Huygens diffuser.

An example of a wrong application of an irregularities wall: In front and rear walls in Auditoria of "Casa da Musica in Porto", were projected on both walls respectively, behind the choir balcony and the wall behind the audience, are corrugated glass that have full-height sinusoidal glass walls, also are called corrugated glass. This glass wall was tested in laboratories of the University of Aachen to know the Scattering magnitudes by frequency.
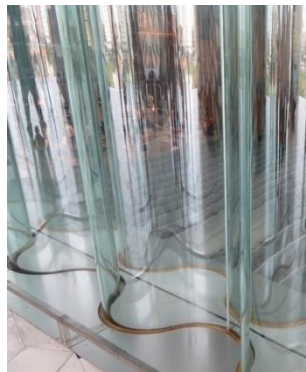
Figure 5: Irregularity glass used in Casa da Musica in Porto.

The great undulation of the glass produces a violation on the basic condition of scattering [1],[16], that is: The diffracted waves radiating from an obstacle which is small compared to sound incident wavelength λ, for: $L_{x,y}$, or w < λ.

Therefore the verification tests of scattering coefficients were useless, because the physical conditions required were not met. On the other hand, because the great undulations dimension of glass has produced largest sound focalizations. They had to put curtains on both sides of the hall, front and rear, and in other parts, it was required because the excess of reverberation time ,RT, of the hall due to excess air volume of Hall V=17500 m3 in relation to the area of hearing audience (N= 1250 seats).

4   Examples of Huygens surface diffusers

4.1   Barcelona concert hall: l'Auditori (1999)

Ceiling definition

The goal of our acoustic design in the roof was to make a diffraction increasing effect using fragmentation of the ceiling by means of great plates near stage to little plates in end of the hall.

We have defined the flat roof with a transverse distribution and longitudinal beams, following a multiple of Fibonacci sequence that produces a fragmentation of the ceiling in a number of different sized coffers between beams.
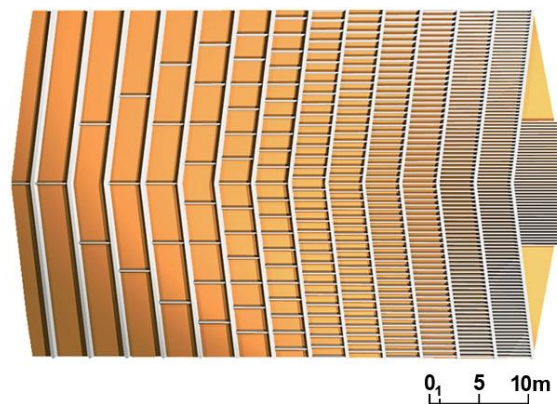
Figure 6: Definition of coffers of ceiling

The acoustical principle behind the ceiling is to provide diffraction, progressively from l0w to high frequencies, were defined according the rules indicated in (1) and (2). It is difficult to judge the amount of diffraction we need on site. We believe that everywhere in the hall, we must have first order mirror reflector where diffraction is only significant in the low frequency bands (63 to 250 Hz). From the middle of the hall to the rear we expect to produce the gradual diffraction together other reflections of medium and high frequencies. In the case of the Concert Hall "L'Auditori Barcelona", the listening experience, or measurements, verifies that none echo and none coloration is produced by any reflections of hall on the stage.

4.2   Szczecin Philharmonic (2015)

4.2.1 Walls

As can be seen, the walls have large, almost rectangular plates of 3.5m x 3 m, each is divided into two sub-triangular plates inclined in opposite space and also opposed to the two sub-plates of adjacent positions. The reflection of sound on each triangular plate is the mirror according to the laws of Snell-Descartes but in different directions. Due to the different direction of the sub-triangular plates, and also due to the different direction that produces the different sub-plates of each rectangle we ensure that the sound is distributed over the concert hall 3D practically in all directions getting an homogeneous space, almost perfectly diffuse sound distribution. We know

that if the wave length of sound was smaller than surface dimensions of each plate, then we will obtain a reflection on each plate. If this were not the case, then diffraction would be significant, something that is much harder to evaluate, and it can completely alter the scheme of sound behaviour within a space. For that the diffraction sound are going to produced, at least the lengths x, y, of the plane reflector must be obey (2).


Figure 7: Ceiling and side walls with diffraction

So, therefore if we're playing with the size of the each plate, we are controlling wavelength of sound that produces a mirror reflection, or the effect diffraction of sound. We understand the diffraction of the sound wave breaking on plate, because the plate has a similar length of the obstacle on which it is breaking, as it is indicated by the Principle of Christian Huygens [4], [5]. In our case the smooth plates of the walls acts as a mirror but also with some diffraction; while the ceiling plates, in the central one of the hall among the amphitheatre and the stage, acts as a mirror sound with certain small diffraction, (as in the plates of the walls of the hall). But there are two areas of high diffraction like as are the zones of ceiling above stage, as also the ceiling of the amphitheatre besides both skylights proposed by architects, which is very beautiful.

Figure 8: Ceiling and side walls with diffraction
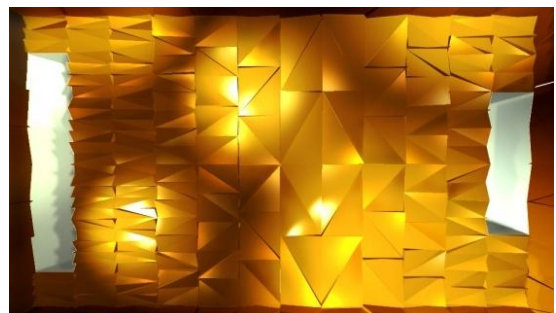
Figure 9: Ceiling with diffraction

4.2.2 Ceiling

The ceiling of the hall has been divided into 12 sections of plates among the skylights in the hall. These zones of the ceiling are more fragmented, have been achieved with a subdivision

that does not follow any mathematical or geometrical law, only has followed the law mentioned before, eqs (1) and (2). The aim of these areas fragmented is obtained by diffraction, a loss of sound energy to give the viewer a feeling of a soft enough sound, but in this case this loss of energy is small. In the central position of the hall, between the stage and the amphitheater, we have placed great plates of dimensions 3.08 x 5.56 m and 3.08 m x 3.70 m, divided by triangular plates, which produce a 3D reflection sound mirror, similar to the plates of the walls. The maximum height of the gap among plates has a deviation of 300 mm. This is so that all walls plates and ceiling of the hall. With this geometrical disposition we are sure to get a good projection of sound from 125 Hz to 4000 Hz frequencies, with mirror reflections and sound diffraction. Therefore all acoustic problems of a hall are avoided, such echoes, echoes flutter, resonances, and so on.

4.2.3 The technical opinion of the experts

The technical opinion of the experts and music lovers is very important. They are who have heard the opening concerts and who have issued their opinion. The press in general says, for example: The symphonic hall, also known as the Sun Hall, may accommodate nearly 1000 people. The magnificent acoustics of the Sun Hall originates from special geometry of the walls and ceiling, developed. All parameters of the symphonic hall (strength, uniformity of sound, delay and lateral energy fractions) produce an effect comparable to the model of such undertakings–the concert hall Musikverein in Vienna.

5   Examples of Huygens volume diffusers (2010)

This case is very important because possibly it is the birth of a new Acoustic branch of the acoustics. The Tonhalle St. Gallen always had, since 1909, serious problems with acoustic, especially on stage. The room was the smallest of the halls of Switzerland, although it was the same architectural and decorative style. In 2009, there arose a new musical experience that started an international competition to repair the acoustic problem of Tonhalle St.Gallen. The Auditorium problem was that its dimensions were small, with relatively low height ceilings, specially on Stage. There the sound problem was very important. The sound of the music in the room was quite bad, but the worst was the stage. The musicians were suffering a loud noise that bothered them deeply. Our team was the winner of this acoustic competition.

Figure 10: **Photos of diffuser after the refurbishment (Architect and Acoustic)**

We proposed to build a grid of plates that seems a labyrinth for sound, which work by acting according to the laws of the principle of Christian Huygens. The plates are floating between the ceiling and the stage, therefore the path process of the wave is:

Diffraction effect of sound in vertical direction, phenomenon that produces in the detail

1. The first trip of the sound, produced by musicians on stage, crashing with the labyrinth grid diffuser

2. The sound waves continue their journey up, experiencing a series of reflections additional to those produced by the room.

3. Then, the sound waves travel up to the top of the labyrinth grid, having produced a second diffraction, when the sound is going up to ceiling.

4. The sound waves recover again to their original state, as predicted by Huygens 'Principle; up to the ceiling of the stage. The sound goes up to ceiling where there is produced a collision, and then the sound returns to the stage, in the opposite direction, producing the same sound effects produced before.

Overall we have got 4 effects of diffraction and 2 effects of production of reflections, in the grid plates, that will increase the free path mean of reflections of the room. Our prediction had thought that each diffraction would produce an energy loss of 1 dB. Therefore we have experimented 4 diffractions, therefore our prediction we hope 4 dB of energy loss. However our experiment measurement was strength, G dB, gave us 3 dB of energy loss. It is a very important reduction. In section 5.2., the experimental measurements are exposed. On the other hand in the hall, we obtained an increase in reverberation time RT. However the effect of increasing reverberation time seems logical, but not were expected by us. We now believe that this was a godsend.
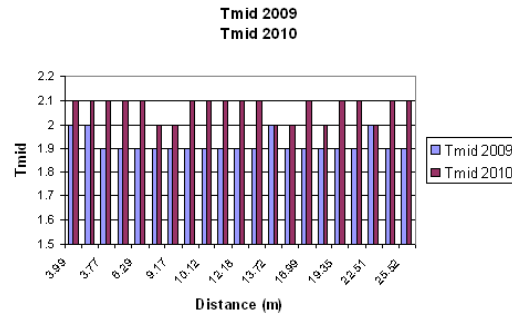
5.1   Summary results

5.1.1 Reverberation Time T30 , and EDT

Audience zone:

a) Reverberation Time T_{30} mean values all sources in audience

Frequency range Mid. 500/1000	$\Delta T_{30}=T_{30}(s)_{2010}-T_{30}(s)_{2009}$
COMPARISON ΔT_{30} $\Delta T_{30}=T_{30}(s)_{2010}-T_{30}(s)_{2009}$	**0.16**

b) Reverberation Time with distance in audience

Tmid 2009
Tmid 2010

Stage zone

a) Reverberation Time T30 mean values all sources on stage

Frequency range Mid. 500/1000	$\Delta T_{30}=T_{30}(s)_{2010} -T_{30}(s)_{2009}$
COMPARISON ΔT_{30} $\Delta T_{30}=T_{30}(s)_{2010} -T_{30}(s)_{2009}$	0.19

b)   b) Early decay time EDT mean values all sources on stage

Frequency range Mid. 500/1000	$\Delta\, EDT=EDT\,(s)_{2010} -EDT(s)_{2009}$
COMPARISON ΔEDT $\Delta EDT=EDT(s)_{2010} -T_{30}(s)_{2009}$	0.34

5.1.2 G : Strenght

Audience zone: Strength G average values all sources in audience

Frequency range Mid. 500/1000	$\Delta G= G_{2010} -G_{2009}$
COMPARISON ΔG $\Delta G=G_{2010} -G_{2009}$	1.15

Stage zone: Strength G dB mean values all sources on stage

Frequency range Mid. 500/1000	$\Delta G= G_{2010} -G_{2009}$
COMPARISON ΔG dB $\Delta G=G_{2010} -G_{2009}$	-2.8 ≈3

5.2 Sumary issues

a) The reality was something different, but it was an excellent result of Strength G loss ≈ -3 dB at mid-frequencies. The important thing about this design is that the musicians were satisfied and felt, as if the roof had been elevating to much higher altitudes. "Now, a flute

sounds like a flute", but before refurbishment it was not happening.

b) Other very important issues are: The sound now is distributed evenly, in 3D, in all areas of the audience and stage. The people of City St. Gallen consider it to be a brilliant and very beautiful solution. Part of the diffracted sound is scattered more or less in all directions.

c) Another phenomenon that happens when we perform acoustic measurements was: The mean value of Reverberation Time T30 and EDT in mid frequencies had increased over the stage, and also in the Auditorium Hall. We thought that it is a logical item, because we know that the Reverberation Time is proportional to the mean free path of the reflections due to the room and the other due to the diffracting labyrinth. Consequently, we believe that we are now closer to creating small spaces of musical audition but large acoustic spaces size.

d) Another example important: When the sound waves are hitting obliquely to the diffuser labyrinth, then the sound the labyrinth see it like a flat surface, so that the sound is reflected to audience zone producing an increase of pressure sound level at 1 dB mid freq.

6 Conclusions

We have tested the Huygens principle applying the knowledge of the nature of sound. We have been very pleased to have solved different cases in which we have had need to think like Christian Huygens did in the past. The mathematics of waves is very complex and has not had enough power to demonstrate the cases exposed. Our imagination has penetrated much deeper into each problem applying the Huygens' Principle.

I'm happy to have opened, to Christian Huygens, the door of old closet of science by acoustic reasons. He has been for me one of the best scientists of all times.

Acknowledgments

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