SCHROEDER DIFFUSORS

Sigrún Ragna Helgadóttir

Mannvit hf
Verkfræðistofa
Grensásvegi 1, 108 Reykjavík, Iceland
sigrunr@mannvit.is

1. INTRODUCTION

Standing in a room or space where the acoustics have been considered, the walls often have a particular shape. This might be a broadcast studio, a concert hall or a church. The reason for some of these particular structures can be traced back to so called "Schroeder diffusors".

2. SCHROEDER

Schroeder was born in 1926 in Germany [1]. In the 1950s, Schroeder was a young student at the University of Goettingen, Germany. At this time, acousticians were measuring frequency response curves of various concert halls, puzzled by the many ups and downs on the curve they got. Schroeder started looking at this and published his first article about this subject in his native language in 1954. Schroeder found out the dips in the response were related to the reverberation time of the hall due to random interference of many overlapping room resonances [2]. He found out the human ear naturally filters these fluctuations out when listening to speech or music. Schroeder worked for Bell Labs for many years and has been a professor at the University of Goettingen since 1969 [3] [4].

2.1 A Study on European concert halls

Schroeder studied sound transmission in reverberant spaces [5] as well as the hearing mechanisms of the ear [6]. In the 1970s, Schroeder undertook a major study of 20 European concert halls [7]. The London Chamber Orchestra agreed to record a piece by Mozart in BBC's studios, a recording free of environmental factors such as echo and reverberation time. Playing this recording from the stage of various music halls with multiple loudspeakers imitated the orchestra actually performing in the hall. The perception at a dummy heads two ears was recorded. The result was played back to a listener, after appropriate handling of the two ear signals, in an anechoic chamber. The listener could now switch between major concert halls in the split of a second and was asked to choose one performance over the other.

Figure 1 shows a picture from the article [8] [9] of the dummy head used to record the two ear signals in a concert hall.

Figure 1. *D. Gottlob, "Dummy", and K.F. Siebrasse (left to right) performing concert hall measurement Photo courtesy [8][9].*

2.2 Findings of the Study

The findings of this study revealed that listeners generally prefer laterally moving sound [10], generally coming from the sides, the walls, giving them a sense of stereophonic effect as opposed to sound coming from the ceiling, hitting the both ears at the same time, giving them a sense of monophonic effect. The conclusion was; narrow concert halls with high ceilings are preferred over wide halls with low ceilings. Others who had discussed the effects of early lateral reflections included West [11], Marshall [12] [13], Keet [14] and Barron [15]. Low ceilings have become more economical in years of air conditioning. If the ceilings are going to stay low, how can these concert halls be made more receptive by audiences?

2.3 Diffusors

Following the study on European Concert Halls, Schroeder released an article in 1975 [16] suggesting "diffusors" with high lateral scattering be placed on the side walls and the ceiling of a concert hall. This would increase laterally moving sound decreasing similarity of signals at the two ears and therefore, improve the acoustis of the hall. To diffuse the sound, Schroeder suggested a surface that would scatter the sound energy uniformly into all directions. For the structure of such a surface, Schroeder used sequences from number theory.

2.4 Sequences from number theory

A "maximum-length sequence", MLS, or Galois sequence, has the property that their power spectrum is completely flat (except for a dip at dc). "Thus, because of the relation between Fourier transform and directivity pattern, a wall with reflection coefficients alternating between +1 and -1, according to such a sequence, would scatter an incident plane wave evenly (except for a dip in the specular direction which corresponds to the dc component in the spectrum)" [16].

Reflection coefficient of +1 can be obtained from a hard wall and a reflection coefficient of -1 can be realized with "grooves" in the wall, a quarter-wavelength deep. This would cause the reflected wave from the groove to be traveling half a wavelength behind the one reflecting from the wall, cancelling the wavelength altogether.

Lining the grooves and the flat surface up using the certain MLS sequence of +1 and -1, the sum of the sound energy reflected from the "diffusor" spreads nicely into all directions instead of the one direction that would occur with a flat surface. Figure 2a shows how an incident wave falls on such a surface spreading into all directions.

This however, works only for that particular wavelength which corresponds to just one particular frequency. In practice, it was found that good diffusion is obtained in a range of wavelengths half an octave below and above the design wavelength.

Figure 2b shows a picture from the very first article on the idea of diffusors [16]. It shows how electromagnetic wave is diffused when hitting a surface with grooves ¼ wavelenght deep following the MLS sequence (- + + - + - + + + + - - - + -).

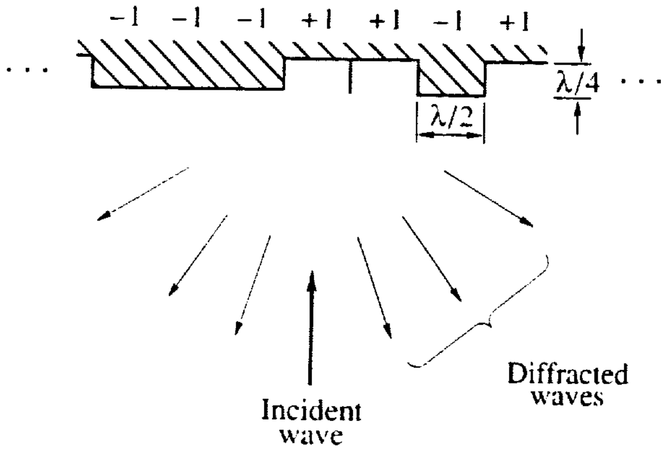

Figure 2a. *Reflection phase grating based on Galois sequence of length 7. Photo courtesy [17].*

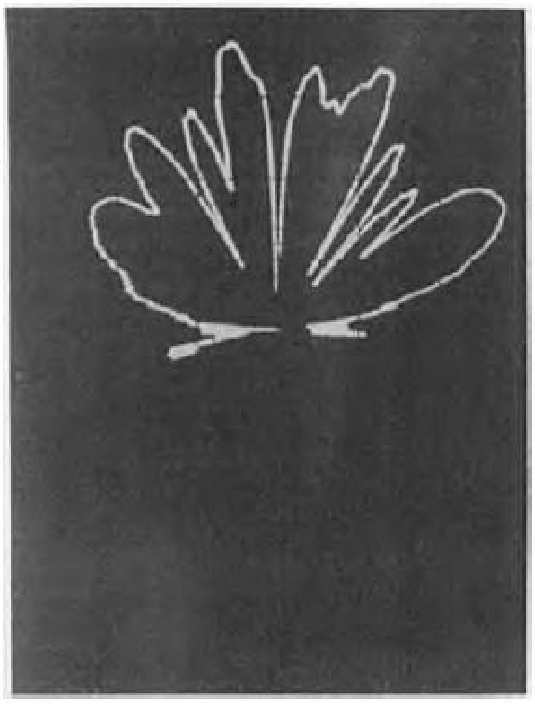

Figure 2b. *Scatter diagram from surface with reflection coefficients alternating in x direction according to one period of maximum-length sequence (- + + - + - + + + + - - - + -). Results obtained in model experiment with electromagnetic microwaves. Photo courtesy [16].*

2.5 Quadratic Residue diffusors

In order for the diffusor to work for more wavelengths, grooves with different depths need to be incorporated. In 1979, Schroeder published an article [18] introducing the use of another sequence with the same unique Fourier transform properties of a flat spectrum, the Quadratic-residue sequences, for diffusor design. The depths of the wells vary from 0 to a little less than half the design wavelength. These diffusors work well for frequencies ranging over 4 octaves coming in from different angles. Figure 3 shows the quadratic residue diffusor from the article. A first application of quadratic-residue diffusors to the design of a large hall is described by Marshall and Hyde [19]. Since then it has been widely used

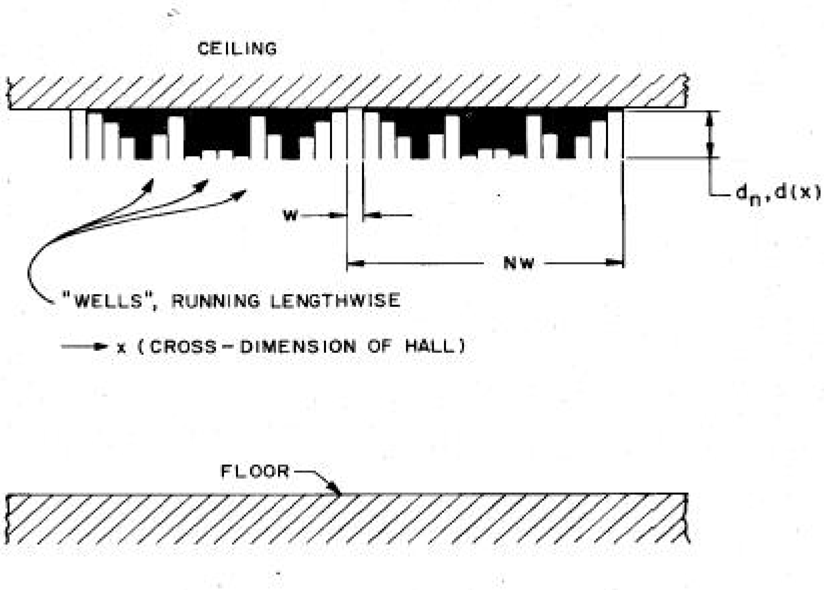

Figure 3. *Lateral cross section through diffusely reflecting ceiling based on quadratic residue sequence. Photo courtesy [18].*

2.6 Manufacturing diffusors

Cox (Acoustics Research Centre, UK) and D'Antonio (RPG Diffusor systems, USA) have studied, manufactured and tested Schroeder diffusors since shortly after the first published articles on them and provide a good overview in [20] [21] and [22]. Figure 4 from [22] [23] shows reflection from an absorptive surface and a flat surface compared to reflection from a diffusing surface. It also shows the temporal response, showing how specular reflection for the absorptive and flat surfaces becomes more diffuse with the use of the quadratic residue diffusor. The spatial response for the absorptive and flat surfaces show a directional reflection whereas the response for the diffusor shows a more uniform reflection.

Acoustical Treatment | *Temporal response* | *Spatial Response*

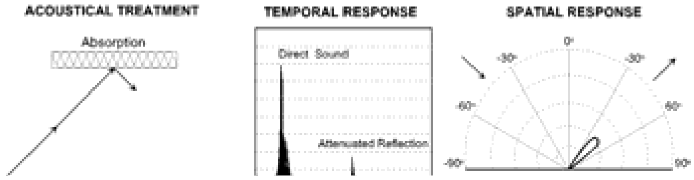

Figure 4a. *Absorption*

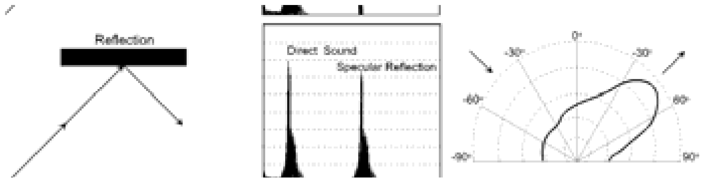

Figure 4b. *Reflection* .

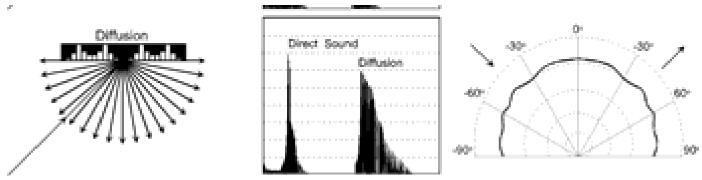

Figure 4c. *Diffusion with Quadratic Residue Diffusor* .

Figure 4. *Spatial and temporal responses of sound reflected from a) a surface with absorption, b) a plane flat surface and c) a diffusor. Photo courtesy [22] and [23].*

2.7 Further advances in diffusor design and applications

The theory behind good acoustics in a concert hall is quite different from the theory of good acoustics in a smaller room. In fact, the literature contains different solutions for different kinds of rooms ranging from concert halls to auditoriums, performing studios, control rooms and the home environment. Schroeder diffusors have been manufactuerd for over 30 years now and many articles have been published [20] [21] [22] [24] [25] [26] [27] [28] [29] [30]. The most widely used diffusors are the quadratic residue diffusors although further experiments have been made based on the MLS sequence and manufactured as well.

2.8 Hybrid surface diffusion: Diffsorber

In later years, for rooms where space is limited, instead of using relatively thick diffusors with grooves in them, thinner diffusors with a sequence of reflective and absorptive material have been studied [20]. In [27], such a diffusor called the binary amplitude diffsorber (BAD) is described in detail. It is basically a flat hybrid surface with the location of the absorbent patches determined by a maximum length sequence (MLS).

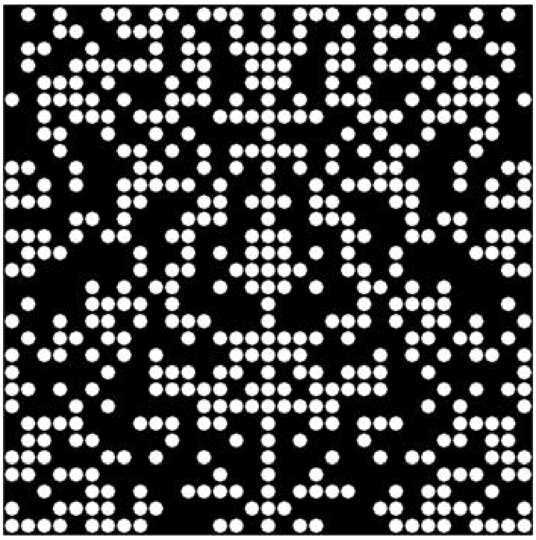

Figure 5. *Planar binary amplitude template. Black areas are reflective and white areas are holes that provide access to absorption. Photo courtesy[31].*

Different sequences from number theory have been studied and tested. The hybrid surface diffusion [22] consists of an absorber, mask and cloth, holes are drilled into the mask when the sequence has a 1, when the sequence has a 0, no hole is drilled. The cloth is used to hide the mask and is transparent to sound waves. Figure 6 shows a picture of the hybrid surface diffusor.

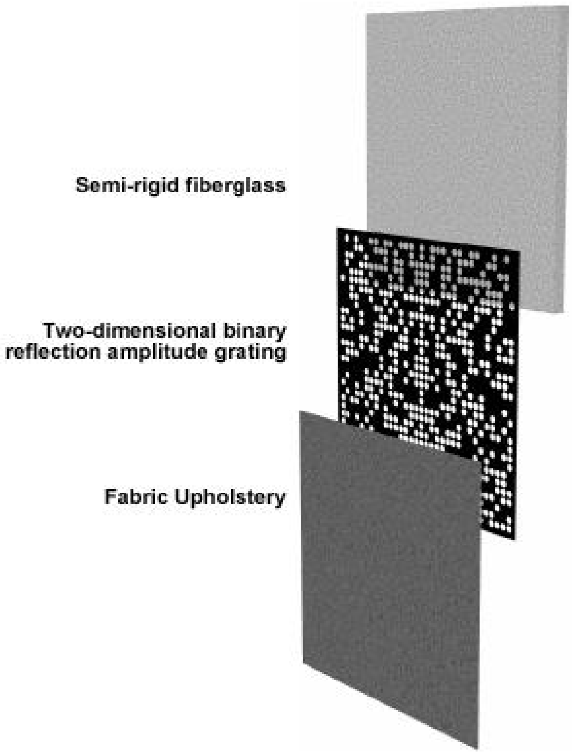

Figure 6. *Construction of a hybrid surface: absorptive core (top), a binary template (middle), and fabric (bottom). Photo courtesy[31].*

2.9 Optimization methods

Optimization methods have been used to create optimized curved surfaces by Cox and D’Antonio [20]. the authors suggest the use of these for large concert halls as they are appealing to the eye and can be matched with the architects ideas on how the hall should look. For sound recording control rooms the authors suggest the use of quadratic residue diffusors.

An application of an optimized curved surface can be seen in the Edwina Palmer Hall, Hitchin, UK [22]. In [22], the authors state the most important question to answer is how much diffusion should be applied, and where diffusors should be used. Figures 7-8 [20] show drawings and use of such a surface, Figure 9 [24] shows the same in 3D, Figure 10 [22] shows the application in the Edwina Palmer Hall.

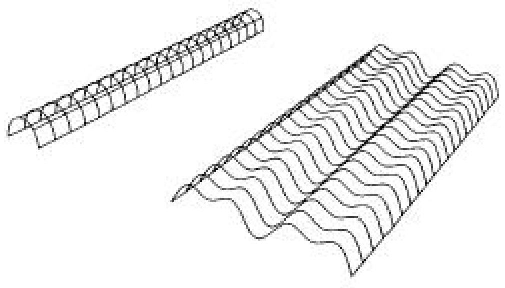

Figure 7. *Optimized surface shapes of two unbaffled curved diffusors with same maximum heigth but different widths. Photo courtesy [20].*

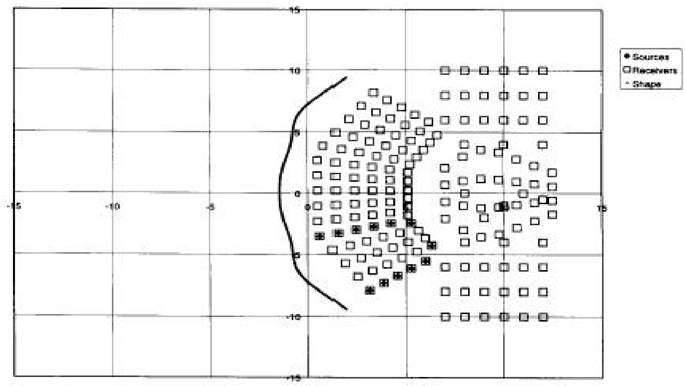

Figure 8. *Optimized amplitude-modulated acoustical shell showing some sources (diamonds) and receivers (squares). Photo courtesy [20].*

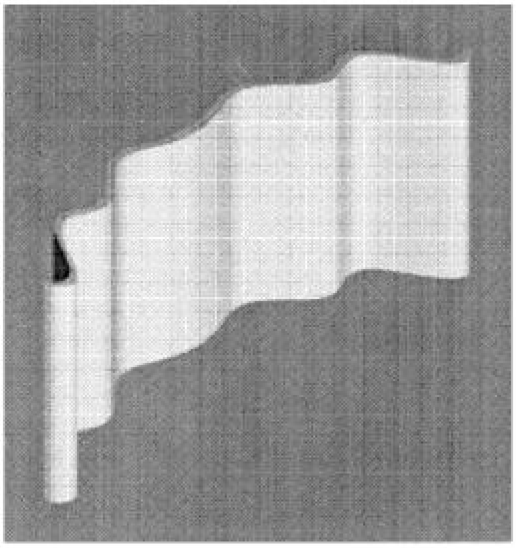

Figure 9. *An amplitude modulated surface to reduce focusing effects. Photo courtesy [24].*

Figure 10. *Optimized curved surface in the Edwina Palmer Hall, Hitchin, UK. Photo courtesy: Arup Acoustics [22].*

Human hearing extends from 20 Hz to about 20 kHz, somewhere between 10 and 11 octaves. The seven most important octaves diffusor designers consider range from 80Hz to 5 kHz [22]. If a diffusor can handle 4 octaves, different solutions need to be considered for remaining frequency ranges.

2.10 Electro-Acoustic Enhancement Systems

The main result from the study on European concert halls was the importance of early lateral reflections. Much effort has been put into development of diffusor design and diffusors will continue to serve an important role in architectural acoustic design. In the mean time, digital technology has advanced to the stage where we can improve the acoustics of a concert hall by increasing early lateral reflections with an electro-acoustical system and even setting the reverberation time to a desired value [32]. Direct sound can be picked up on stage and, after going through a digital signal processing system, early lateral reflections can be created electronically as well as changing the reverberation time of the hall, both done in a way that it seems natural. An Electro-Acoustical System gives one the freedom of selecting an appropriate acoustical environment that suits a certain performance [32]. This is beneficial for spaces where we don´t have the option of a narrow, high ceiling concert hall, or an already existing enclosure where space is limited for improvements.

3 CONCLUSIONS

Many studies have been done on concert hall acoustics to pinpoint problems and the design of diffusors has evolved to fix those problems found. The change in architecture has taken away the acoustic quality of the old, narrow, high ceiling concert halls where the decorations acted as natural diffusors. This changed with new architecture style of flat surfaces, lower ceilings with the birth of air conditioning systems, and wider halls to accommodate more people. A lot of work has been done in the field, improving the acoustics of concert halls, auditoriums, broadcasting studios, performing studios and home environments. A study on European concert halls found the reason for bad acoustics to be the lack of early lateral reflections. In today's wide, low ceiling concert halls, early lateral reflections are accomplished with the use of diffusors on walls and in ceilings, improving the acoustics of the hall. With advancements in Electro-Acoustical Engineering, digital technology can also be used to improve acoustic quality of spaces and has become more commonplace.

4 REFERENCES

[1] http://www.physik3.gwdg.de/~mrs/Vortraege/Remembering-the-Good-Days-at-Bell-Laboratories-2004/index.html

[2] Schroeder, M. R., Fractals, Chaos, Power Laws - Minutes from an Infinite Paradise, 1991, W.H. Freeman and Company, New York

[3] http://www.physik3.gwdg.de/~mrs/

[4] http://www.physik3.gwdg.de/%7Emrs/mrs/main.html

[5] Schroeder, M. R., Digital Simulation of sound transmission in reverberant spaces, Journal of the Acoustical Society of America 47 (2): 424& 1970.

[6] Schroeder, M. R., Models of hearing. Proceedings of the IEEE 63 (9): 1332-1350 1975.

[7] Schroeder, M. R., Comparative Study of European concert halls: correlation of subjective preference with geometric and acoustic parameters, Volume: 56 Date: 1974 Pages: 1195-1201 Journal J. Ac. Soc. Am

[8] Schroeder, M. R., Acoustics in human communications: Room acoustics, music, and speech, Volume: 68 Date: 1980 Pages: 22-28 Journal J. Ac. Soc. Am

[9] Schroeder, M. R., Towards better acoustics for concert halls, Volume: 33 Date: 1980 Pages: 24-30 Journal Physics Today

[10] Schroeder, M. R., Listening with 2 ears, Volume: 10 Issue: 3 Date: 1993 Pages: 255-280 Journal Music perception

[11] West J.E., Possible Subjective Significance of the Ratio of Height to Width of Concert Halls, Volume: 40, Date: 1966, 1245, J. Ac. Soc. Am

[12] Marshall, A Note on the Importance of Room Cross-Section in Concert Halls, Volume: 5, Date: 1967, Page: 100, Journal of sound and vibration

[13] Marshall, Concert Hall Shapes for Minimum Masking of Lateral Reflections, Proc.6th ICA, Tokyo, Paper E-2-3. Date: 1968
[14] Keet, W.V., The Influence of Early Lateral Reflections on the Spatial Impression, Proc.6th ICA, Tokyo, Paper E-2-4 Date: 1968
[15] Barron, M., The Subjective Effects of First Reflections in Concert Halls – The Need for Lateral Reflections, Volume: 15, Date: 1971, Page: 475-494, Journal of sound and vibration
[16] Schroeder, M. R., Diffuse sound reflection by maximum-length sequences, Volume: 57 Date: 1975 Pages: 149-150 Journal J. Ac. Soc. Am
[17] Schroeder, M. R., Sequences from number theory for physics, signal processing, and art, Volume: 49 Date: JAN-FEB 2003 Pages: 97-108 Journal Acoustical physics.
[18] Schroeder, M. R., Binaural dissimilarity and optimum ceilings for concert halls: more lateral sound diffusion, Volume: 65 Date: 1979 Pages: 958-963 Journal J. Ac. Soc. Am.
[19] Marshall, A. H., Hyde, J. R., Evolution of a Concert Hall: Lateral Reflection and the Acoustical Design for Wellington Town Hall, Vol.63, Date: 1978, S36 (A), J. Ac. Soc. Am.
[20] D'Antonio, P., Two decades of sound diffusor design and development - Part 1: Applications and design, Volume: 46 Issue: 11 Date: 1998 Pages: 955-976 Journal of the Audio Engineering Society
[21] D'Antonio, P., Two decades of sound diffusor design and development - Part 2: Prediction, measurement, and characterization, Volume: 46 Issue: 12 Date: 1998 Pages: 1075-1091 Journal of the Audio Engineering Society
[22] Cox, Engineering art: the science of concert hall acoustics, Volume: 28 Issue: 2 Date: 2003 Pages: 119-129 Journal Interdisciplinary science reviews : ISR.
[23] RPG Diffusor systems, http://www.rpginc.com/news/seminars/Diffuse_Seminar_2007_School_Acoustics.pdf, 2007
[24] D'Antonio, P., Diffusor application in rooms, Volume: 60 Issue: 2 Date: 2000 Pages: 113-142 Journal Applied acoustics. Acoustique applique´. Angewandte Akustik.
[25] D'Antonio, P., Surface diffusion coefficients for room acoustics: Free-field measures, Volume: 108 Date: 2000 Pages: 1710-1720, J. Acoust. Soc. Am
[26] D'Antonio, P., AES information document for room acoustics and sound reinforcement systems - Characterization and measurement of surface scattering uniformity, Volume: 49 Issue: 3 Date: 2001 Pages: 149-165 Journal of the Audio Engineering Society
[27] D'Antonio, P., Trenary and quadriphase sequence diffusers, Volume: 119 Date: 2006 Pages: 310-319 Journal J.Acoust. Soc. Am
[28] Cox, Acoustic phase gratings for reduced specular reflection, Volume: 60 Issue: 2 Date: 2000 Pages: 167-186 Journal Applied acoustics. Acoustique applique´. Angewandte Akustik.
[29] Cox, Room sizing and optimization at low frequencies, Volume: 52 Issue: 6 Date: 2004 Pages: 640-651 Journal of the Audio Engineering Society.
[30] Cox, A tutorial on scattering and diffusion coefficients for room acoustic surfaces, Volume: 92 Issue: 1 Date: 2006 Pages: 1-15 Journal Acta acustica united with Acustica.
[31] RPG Diffusor systems, Research & Development, Research Topics: Binary Amplitude Diffsorber Part 1, http://www.rpginc.com/research/6i2.htm
[32] D'Antonio, P., Diffuse Reflections, Volume 12, Issue 1, 2007