ACOUSTIC DIFFUSERS: THE GOOD, THE BAD AND THE UGLY

T J Cox, Salford University

1. ABSTRACT

The modern acoustic diffuser has an ability to attract comment, some say they sound good, some say they sound bad; some designs look beautiful and others are ugly. Proper amounts of the right diffusion are credited with contributing to spectacular acoustics, too much of the 'wrong' diffusion gets blamed for ruining one hall, while the lack of scattering in another is held responsible for a poor acoustic. How can there be so many contradictions? Is it just a matter of personal taste, or is there some underlying physics and psychoacoustics that needs to be better understood? It is almost 30 years since Schroeder published his seminal paper on diffuse reflections from maximum length sequences, and despite much research effort since then, issues about when and why diffusers should be used, and what kind of surfaces should be used, remain to be fully answered. In this paper, some of the myths surrounding diffuser application will be explored. The current state of the art in the design will be presented and future questions that need answering will be posed.

2. INTRODUCTION

Over the centuries, architectural tastes have changed, leading to a visual change in interior design, which has resulted in a physical change in the acoustics of rooms. In grand palaces and concert halls built before the twentieth century, statuary, relief work and other ornamentation used to be commonplace, providing ample surface scattering, and presumably a more diffuse sound field. This style was replaced in the twentieth century by a simpler look. Many auditoria and rooms from the twentieth century contain large flat surfaces, which in turn leads to more specular and less diffuse reflections. There is also a suggestion, that with the greater precision of twentieth century engineering, and consequently these flat areas became more precise than the more hand-crafted older building, leading to more exacting specular reflections.

Towards the end of the last century, there appeared to be an increase interest in the use of scattering surfaces within concert halls. Certainly there was an explosion in their use in listening and studio control rooms. One catalyst for this was Schroeder's pioneering design of diffusers[1], such as the Quadratic Residue Diffuser (QRD)[2], which gave acousticians the possibility of designing diffusers with known acoustic characteristics. This was further helped by the successful application of these diffusers by Marshall and Hyde in the Michael Fowler Centre, New Zealand[3,4] and the work by D'Antonio[5] who utilized the designs in small rooms to exploit concepts such as Live End Dead End (LEDE®)[6] and Reflection Free Zone (RFZ™)[7].

Informal conversations with practitioners have indicated that diffusers, either the presence or lack of them, are sometimes cited as reasons for the acoustics of a space failing to meet expectation. It is hard to know how much weight to put on these opinions, because they are usually not borne out by psychological measurement using test juries and following scientific methods, but are simply individual opinions, albeit from recognized experts. Scientific methods have only infrequently been brought to study the influence of diffusers on the sound propagation and the perception of the resulting acoustic, so it is hard to give conclusive evidence for the value of diffusers. For this reason, designers have tended to fall back of intuition and precedence. However, one of the reasons for the confusion about whether diffusers have been effective in a particular space, might have arisen because some things that look like diffusers, don't have the characteristics of a sound diffuser.

3. WHEN IS A SURFACE A DIFFUSER?

While this might seem at first a rather trite question, it is important that this is clearly defined, because currently some surfaces that claim to be diffusing are not. If people are going to complain about a diffuser ruining a hall, it is important to be clear that what is being used is really a diffuser. Not all corrugated surfaces are proper diffusers.

3.1 TEMPORAL AND SPATIAL DISPERSION

The original work by Schroeder examined the spatial dispersion of sound generated by diffusers. Polar responses were examined to see how sound was distributed at specific frequencies into grating lobes. Since then, the methods have evolved to look at spatial dispersion in all directions, in one-third octave bands[8]. Spatial dispersion is a useful concept when examining coverage over audience and stage areas, but often diffusers are used to deal with defects at certain positions in a hall, especially coloration and echoes[9]. This is especially true in small spaces such as studio monitor rooms, where the diffusers are being used to suppress strong first order reflections. If a diffuser is being used to deal with coloration (for instance, comb filtering), than there is a need for both spatial and temporal dispersion to be considered. For example, Figures 1 and 2 show the time and frequency response for scattering from a single semi-cylinder. The single semi-cylinder produces excellent spatial dispersion, but as can be seen from Figure 1, there is no temporal dispersion. Consequently, the frequency response of the combined incident and reflected sound shows a comb filtered response due to the similarity between the two sounds. This might be why the sound from semi-cylinders has been disliked. The only study to look at this scientifically was a small scale study by Lee[10], who came to the conclusion that reflections from modulated surfaces are preferred to those from simple curved surfaces.

Figure 1 The Impulse response for sound reflected from a semi-cylinder

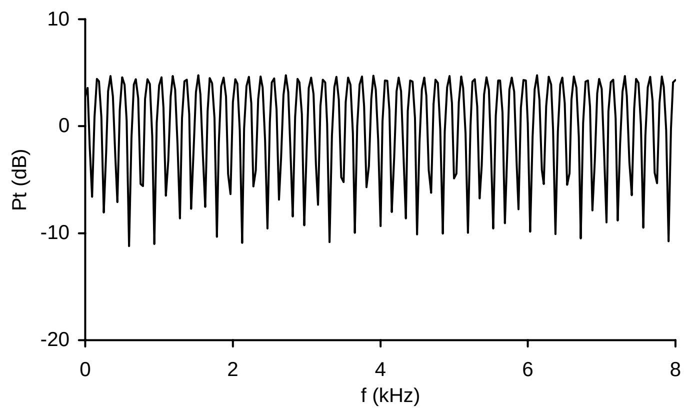


Figure 1. The frequency response for sound reflected from a semi-cylinder interfering with the direct sound.

Consequently, a good diffuser needs to generate spatial AND temporal dispersion. While a Schroeder diffuser may be designed purely for its spatial scattering properties, it naturally generates temporal dispersion because of its complex geometry (provided the period width is wide enough). In the case of semi-cylinders, arranging them in a periodic array may not be sufficient to disperse the temporal response, and some form of randomised arrangement is probably needed.

Another critical application for highlighting the differences between spatial and temporal dispersion is stage shells. The side and rear walls of stages are sometimes flat, and sometimes have diffusing surfaces. While there is evidence that diffusing stage shells are useful[11], many practitioners still favour flat surfaces.

Overhead canopies can also have flat or curved surfaces. Consider the case of a stage canopy which has very little open area, these are probably more common in America than in Europe. An interesting misconception is that it is the spatial dispersion created by overhead diffusers which is of sole importance in this case. With large flat surfaces overhead and no significant gaps, there is no difficulty in gaining specular reflections between two points on the stage. Consequently, the spatial dispersion offered by the diffuser is not what is useful, because the reflected sound energy is probably sufficient at all positions on the stage. What is important, however, is that there is temporal dispersion, removing the strong comb filtering that would otherwise result from the interference between the strong overhead reflection and the direct sound. This comb filtering would make it difficult for musicians to create a good tone.

3.2 TRIANGULAR PRISMS: DIFFUSERS?

Surface relief made from pyramids or triangular prisms have interesting acoustic properties, depending of the angle of the sides of the surface, the reflections from this surface can be specular, concentrated in a few major lobe directions or dispersed[12]. When the issue of periodic arrangement of these surfaces is considered, the picture becomes more complicated.

Triangular prisms have been favoured by some as a treatment for stage houses. But the angles chosen for the triangles are such that the spatial and temporal dispersion is often limited. For instance, Figure 4 shows the scattering from a triangular prism with a 30º side angle. In this case, what is generated is two sideways propagating lobes, and it is unlikely that this is the dispersion pattern intended by the designers. Scientific papers have appeared where such surfaces have been described as diffusers, and this is misleading.

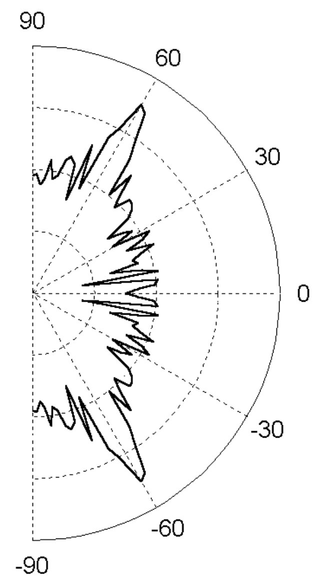


Figure 3, reflection from a 30º triangular prism predicted using a Boundary Element Model[12]

3.3 REPEAT DISTANCE TOO SMALL

Figure 4 shows a popular diffuser, which as the title of the patent suggests, is designed to be a *"two dimensional sound diffusor"* [13]. In the direction marked x in the figure, there are plenty of height variations, and it is reasonable to assume that dispersion is generated, as indeed is proved by the measurement data in the patent, and reproduced in the middle of Figure 4. In the direction y, however, the surface has a very small repeat. This means that the surface can not generate any grating lobes, and so dispersion is poor. This is also shown in Figure 4 at the bottom. Consequently, the name of the patent is rather misleading, this is actually a one dimensional sound diffuser for a significant bandwidth.

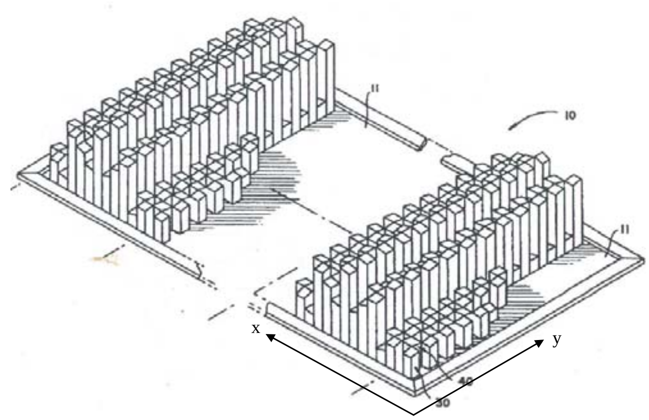
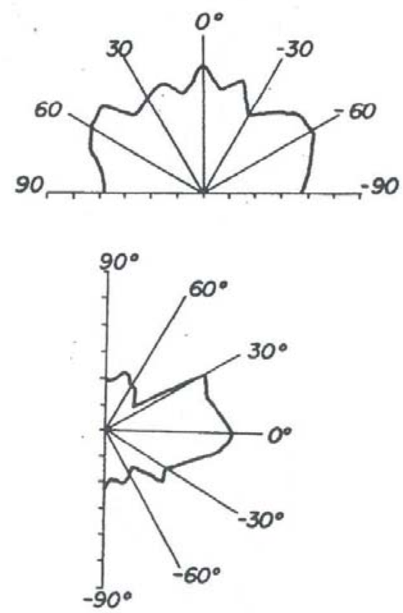


Figure 4. A 'two-dimensional' sound diffuser[13], and its scattering in two directions.



Over recent years, many methods have been developed for extending the repeat distance of diffusers. If the aim of a diffuser is to generate reflected energy at oblique angles, it is necessary for the diffuser to have a period width (or repeat distance) larger than the wavelength of the lowest frequency where scattering is required. For a periodic device, having the width equal to the wavelength means that three reflection lobes are generated in the directions -90º, 0º and 90º (relative to the surface normal). Some so-called diffusers, produce no significant scattering over the bandwidth expected, because the bandwidth has been assumed to be defined by the diffuser depth, and no account of the period width has been taken.

Takahashi and Takahashi[14] investigated the audibility of periodicity for triangular prisms. They concluded that the effects of periodicity were audible, but more work is needed to examine more effective diffusers, and to translate the answers into useable design guidelines

3.4 SPARSE GRATING LOBES

Another problem with repeat distance, is that it can lead to a frequency bandwidth where there are a small number of lobes directed into only a few directions. An example of this is shown in Figure 5 in red. So if this diffuser was being used to treat an echo problem, only a nominal 5dB reduction in the specular reflection lobe is being achieved, and this might not be sufficient to remove the echo. The case shown is where the wavelength is of the same order of size as the period width. Ideally, the period width should be many times greater than the wavelength, so either a large number of lobes exist or there is no periodicity and therefore no lobes at all.

To allow an extension of repeat distance without the need for manufacturing a single large surface element, modulation schemes have been designed which achieve large area coverage from a few base shapes. Early work in this area by Angus concentrated on Schroeder diffusers[15,16]. Two different Schroeder diffusers are used, say one being an N=5 QRD and the other an N=7 QRD. These diffusers are then arranged, with the order of the diffusers being determined by a pseudo-random number sequence with good aperiodic autocorrelation properties to minimize periodicity effects. It is more efficient for manufacture if a single asymmetric base shape can be used, as might be achieved using a primitive root sequence. The method can also be extended to extruded and multi-dimensional curved surfaces[17] as shown in Figure 6.

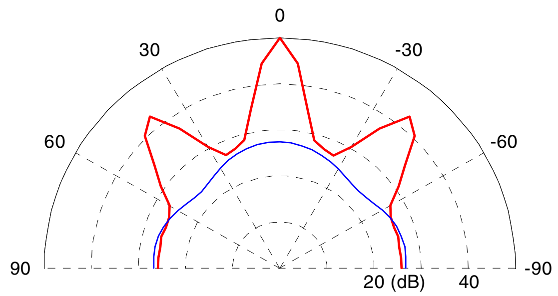


Figure 5 Scattering from a single semicylinder (blue), and 12 of the same semi-cylinders (red)[17].

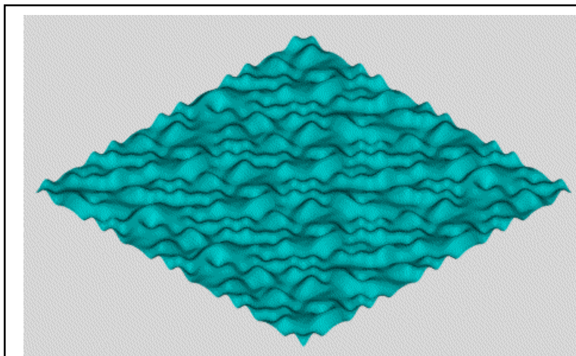
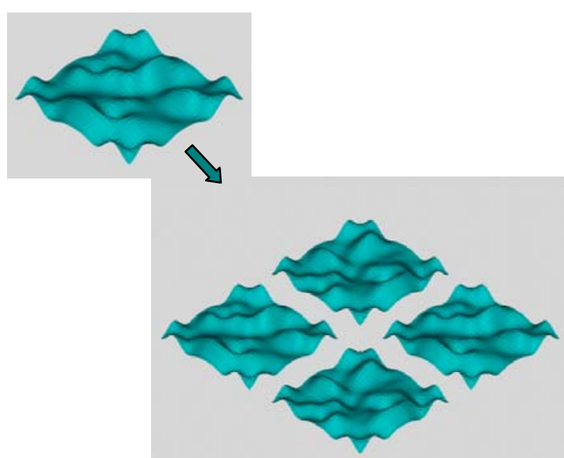


Figure 6. Seamless tiling of a single base shape (below), a 4x4 array (above)



4. IS A QRD DIFFUSER UNIQUELY MAGICAL?

There appears to be a mystique surrounding the QRD, with it being assumed that these surfaces produce uniquely magical reflection characteristics that can not be achieved by any other surface profile. Indeed, a quick search on the Internet reveals that most companies manufacturing diffusers have number theoretic designs in their catalogue.

Since the invention of the Schroeder diffuser, many papers have been produced to show weaknesses in the design, and usually providing solutions to the problem. These are reviewed in references 12 and 18. Issues include:

- Critical or flat plate frequencies at which the surface behaves like a flat plate and produces no dispersion;
- Narrow diffusers have performance limited by period width - see above;
- Poorly made diffusers or diffusers covered in fabric can be absorbing;
- Optimal diffusion at discrete frequencies is not the same as optimal diffusion across a wide bandwidth;
- Grating lobes all with the same energy is not the same as having even scattering in all directions unless there are a large number of lobes.

This list excludes other misuses of the concept, such as not understanding what a quadratic residue sequence is. To quote from one web site:

*“The ********** is a high-performance quadratic residue diffuser that employs a series of 15 wells of specific depths to break up and scatter acoustic energy.”*

A quadratic residue design must be based on a prime number, otherwise it is no better than a diffuser based on the lowest factors, in this case 3 an 5. Even stranger, the picture of the diffuser on the web site shows it to have 16 wells!

Over the years, a few practitioners have been critical of the sound produced by arrangements of number theoretic diffusers. However, these criticisms have usually centred on the most simple low-N designs, and have ignored the fact that over the years a great deal more has been learnt about the scattering ability of the surfaces. Maybe the artefacts being heard were due to critical frequencies or periodicity lobes? Unfortunately, as these observations have not been supported by an investigation following a scientific method, it is hard to draw any conclusions; it isn’t even known whether other people can hear these artefacts or not.

But to return to the question of this section, is the QRD a unique surface, and is it true that no other design can be as good? The answer is, of course, no. The ingenuity of Schroeder was to design a surface where mathematical principles could be used in the design. By arranging the surface as a series of wells, the diffuser could be modelled as a flat surface of varying impedance. This then enables some relatively simple mathematics to be applied to the surface, which result in the well known design equations. So the surface construct is a convenience to achieve a mathematical aim, it is not unique in being able to produce scattering. Any corrugated surface has the potential to break up reflected wavefronts, and so produce scattering. The problem is that once a design moves away from a series of wells, to steps, curved or fractal constructions, then the simple design equations are no longer applicable. In that case, a standard engineering solution, numerical optimisation, is used whereby a computer searches for the best possible diffuser shape. At this point the surface can be any arbitrary shape[19,20,21].

5. IS LOTS OF DIFFUSION GOOD OR BAD?

Acoustic aberrations such as image shift, colouration and echoes can be removed by using diffusers. There is enough evidence from precedence to show that diffusers can be effective in treating these defects, and a few scientific studies have also demonstrated this[10,14,11]. So why not just cover the whole auditoria with diffusing surfaces? Ignoring what the architect might think of the concept and cost, all one can currently conclude is that there is very little data to say what the effect of including large scale diffusion on the acoustic generated is. There is a fear among some that this would remove spatial cues that are present in early reflections, leading to an imprecise sound, but no one has measured such effects.

Hann and Fricke[22,23] showed that in the most highly acclaimed concert halls in the world ,the Surface Diffusivity Index (SDI), which is a global qualitative characterization of surface diffusion, correlates very highly with an Acoustic Quality Index (AQI). SDI was determined from a visual inspection of the surface roughness. This work requires further confirmation, and many are skeptical about the finding on the grounds that the test method and evaluation seem too simple.

Chiles[24] investigated the effects of scattering surfaces on monaural measures in concert halls. He found that adding scattering surfaces made the sound field more diffuse, and the most effective locations for doing this were at the front or the rear of the hall. Adding diffusers to the side walls increased the backscatter towards the stage, decreased the clarity towards the rear of the concert hall, and so was potentially detrimental to quality. The work needs further extending to look at spatial aspects of the sound such as early and late lateral energy, and also the effects on coloration.

Torres et al[25] examined changing the amount of diffuse reflections in a computer model and testing the audibility of changes. They found that changes in the amount of diffuse reflections were audible, but as the acoustic fields were predicated using computer models that can only approximately model the effects of scattering, and so it is hard to conclude much more from this work when considering real rooms.

Consequently, there is a need for more studies to investigate how much diffusion is needed and where is should be applied. In the recent RADS symposium (International Symposium on Room Acoustics: Design and Science, Japan, 2004), round table discussions implied that many favoured ‘moderate’ diffusion. It was unclear, however, what moderate diffusion means. Does this mean moderate scattering but over a wide bandwidth? Or does it mean moderate surface corrugation, which would imply significant scattering only above mid-frequencies?

6. DO DIFFUSERS CAUSE BAD ABSORBPTION?

Not long after Schroeder diffuser's were invented, there were rumours that these surfaces cause significant absorption. By their very nature, Schroeder diffusers contain quarter wave resonant structures, and consequently it would be expected that some absorption would occur at and around the resonant frequencies. The absorption coefficients reported in some of the literature, however, greatly exceeds that which can be attributed to quarter wave resonance alone. Notably, Fujiwara and Miyajima[26] measured absorption coefficients ranging from 0.3 to 1, and Commins, Auletta and Suner [27] measured coefficients peaking at about 0.5. These high absorption coefficients are in marked contrast to random incidence absorption coefficients measured on commercial samples[28]. The contradiction can probably be explained by construction quality; Fujiwara[29] later publication showed that the excessive absorption seen in his earlier publication was caused by poor construction.

Provided Schroeder diffusers are well sealed and made from non-absorbing material, there is no reason why absorption should be excessive. However, it is very important that the surfaces are not covered, because excess absorption then occurs due to high particle velocity near the well entrances.

7. DO DIFFUSERS HAVE TO LOOK UGLY?

When Schroeder invented his diffusers, they fitted in with some of the artistic trends of the day. With abstraction to the fore, the fins and wells formed elements in keeping with the style of the day. But in the intervening decades, tastes have moved on. Architecture has been greatly influenced by advances in engineering to allow previously unimaginable shapes to be constructed. Landmark buildings are becoming sculptured with complex geometries and curved forms. To many, Schroeder diffusers no longer match the style required. Fortunately, with optimisation[12] it is possible to design arbitrary shaped diffusers, echoing the ability of architects to seeming work with any shaped building. Diffusers can usually be created which have harmony with the architectural style of the building[30]. There are even developments in flat diffusers[12], which may satisfy the whims of minimalist architects; although these are only currently useable where absorption is also required.

8. CONCLUSIONS

Acoustic diffusers have changed considerably in the last three decades. There are many examples of successful applications improving the acoustics of a wide variety of rooms. Much has been learnt about how they should be designed, measured and predicted. However, considerable research remains. Over the last century, the design of rooms has moved from mostly following precedence, to a system by which scientific and engineering principles can be used to maximise the chance of building acoustically-successful spaces. The story of diffuser development is following the same path. Hopefully in the near future good quality scientific knowledge can be used to avoid bad and ugly diffuser designs and applications.

9. REFERENCES

[1] M. R. Schroeder, “Diffuse sound reflection by maximum-length sequences,” J.Acoust.Soc.Am., 57(1), 149-150, (1975).
[2] M. R. Schroeder, “Binaural dissimilarity and optimum ceilings for concert halls: more lateral sound diffusion”, J.Acoust.Soc.Am., 65, 958-963, (1979).
[3] A. H. Marshall and J. R. Hyde, “Some practical considerations in the use of quadratic residue diffusing surfaces,” proc. 10th ICA, Sydney, paper E7.3, (1980).
[4] A. H. Marshall, J. R. Hyde and M. F. E. Barron, “The acoustical design of Wellington Town Hall: design development, implementation and modelling results,” proc. IoA(UK), Edinburgh, (1982).
[5] P. D’Antonio and J. H. Konnert, “The Reflection Phase Grating Diffusor: Design Theory and Application”, J.Audio Eng.Soc., **32**(4), (1984).
[6] D. David and C. Davis, “The LEDE concept for the control of acoustic and psychoacoustic parameters in recording control rooms,” J.Audio Eng.Soc., **28**, 585-595, (1980).
[7] P. D’Antonio and J. H. Konnert, “The RFZ/RPG approach to control room monitoring,” proc. Audio Eng.Soc., Preprint 2157 (I-6), (Oct. 1984).
[8] AES-4id-2001, “AES Information document for room acoustics and sound reinforcement systems – characterisation and measurement of surface scattering uniformity,” J.Audio Eng.Soc., **49**(3), 149-165, (2001).
[9] P. D'Antonio and T. J. Cox, "Diffusor application in rooms," Appl. Acoust., **60**(2), 113-42, (2000).
[10] E. J. Lee, “Effects of surface textures of choral reflectors,” proc. 16th ICa Seattle WA, III, 2149-2150, (1998)
[11] P. D'Antonio, “Performance acoustics: the importance of diffusing surfaces and the variable acoustics modular performance shell,” proc, 91st Audio Eng.Soc. convention, New York, preprint 3118 (B-2), (October 1991).
[12] T. J. Cox and P. D'Antonio. “Acoustic absorbers and diffusers: Theory, design and application,” Spon Press. (2004).
[13] US Patent, 5,160,186, “Two dimensional sound diffusor,” (1990)
[14] D. Takahashi and R. Takahashi, "Sound fields and subjective effects of scattering by periodic-type diffusers," J. Sound Vibr., **258**(3), 487-97, (2002).
[15] J. A. S. Angus, "Using grating modulation to achieve wideband large area diffusers," Appl. Acoust., **60**(2), 143-65, (2000).
[16] J. A. S. Angus and C. I. McManmon, "Orthogonal sequence modulated phase reflection gratings for wide-band diffusion," J. Audio Eng. Soc., **46**(12), 1109-18, (1998).
[17] P. D'Antonio and T. J. Cox, "Aperiodic tiling of diffusers using a single asymmetric base shape", ICA2004, Japan, MO2.B.3, (2004).
[18] T. J. Cox and P. D'Antonio, "Schroeder diffusers: A review," Building Acoustics, (2003).
[19] T. J. Cox, "The optimization of profiled diffusers," J. Acoust. Soc. Am., **97**(5), 2928-36, (1995).
[20] T. J. Cox, "Designing curved diffusers for performance spaces," J. Audio Eng. Soc., **44**(5), 354-64, (1996).
[21] T. J. Cox and P. D'Antonio, "Fractal sound diffusers", 103rd Convention of the Audio Engineering Society, NY, Preprint 4578, Paper K-7, (1997).
[22] Haan, C.N. & Fricke, F.R., “Surface Diffusivity as a Measure of the Acoustic Quality of Concert Halls”, Proc. Of Australia and New Zealand Architectural Science Association Conference, Sydney (1993).
[23] Haan, C.N. & Fricke, F.R., “The Use of Neural Network Analysis for the Prediction of Acoustic Quality of Concert Halls”, Proc. Of WESTPRAC V’94, 543-550, (Seoul 1994).

[24] S. Chiles, Ph.D. Thesis, University of Bath, (2004).
[25] R. R. Torres, M. Kleiner and B. I. Dalenback, "Audibility of "diffusion" in room acoustics auralization: An initial investigation," Acustica, **86**(6), 919-27, (2000).
[26] K. Fujiwara and T. Miyajima, “Absorption characteristics of a practically constructed Schroeder diffusers of quadratic residue type,” Applied Acoustics. Technical Note. 35. 149-152, (1992).
[27] D. E. Commins, N. Auletta, B. Suner, “Diffusion and absorption of quadratic residue diffusers,” Proc.I.O.A. 10(2), 223-232, (1988).
[28] T.J.Cox and P. D'Antonio, "Absorption by surface diffusers", proc. IoA(UK), Auditorium 2002, London, (2002).
[29] K. Fujiwara, “A study on the sound absorption of a quadratic-residue type diffuser,” Acustica, 81 370-378. (1992).
[30] T. J. Cox and P. D’Antonio, "Holistic diffusers", proc. IoA(UK), 21(6), 201-6, (1999).