

Holistic Diffusers

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1. INTRODUCTION

At the turn of the last century, when Sabine was carrying out his pioneering work in room acoustics, auditoria benefited from the inclusion of surface diffusion, as it was the fashion of the day to use ornamentation and relief decoration. As the century progressed, modern architectural design tended to move towards cleaner lines for aesthetic reasons and also cost constraints. This greatly reduced the naturally occurring surface diffusion in many auditoria. The century has also seen a revolution in our understanding of acoustic design. While perfection can not be guaranteed for new auditoria, the chances of disaster are much reduced. Of relevance to this paper, in the last few decades there has been a revolution in the design of sound diffusers, built on the pioneering work of Schroeder. In the past the sound diffusion effects of ornamentation and relief decoration was ill defined, but Schroeder began the process of designing surfaces with known acoustic properties. Now there is a much greater body of academic knowledge about the design, characterisation and application of diffusing elements, although that is not to say that many challenges do not still exist for the next century. This paper looks at current design techniques with an emphasis on a holistic approach combining acoustics and visual aesthetics. Now it is possible to meet visual requirements as well as acoustic criteria to try and make modern diffusing elements an integral part of architectural design, in much the same way as ornamentation served a dual purpose in previous centuries.

2. DESIGN

2.1 Schroeder

In the 1970s Schroeder¹ introduced a new type of profiled sound diffuser, generically termed a Schroeder diffuser. The top image in Figure 1 shows a standard quadratic residue surface (QRD), the bottom image shows a more modern design² which combines the number theory and fractal concepts to produce a wider bandwidth surface while avoiding excess absorption. The design of Schroeder marked a large step

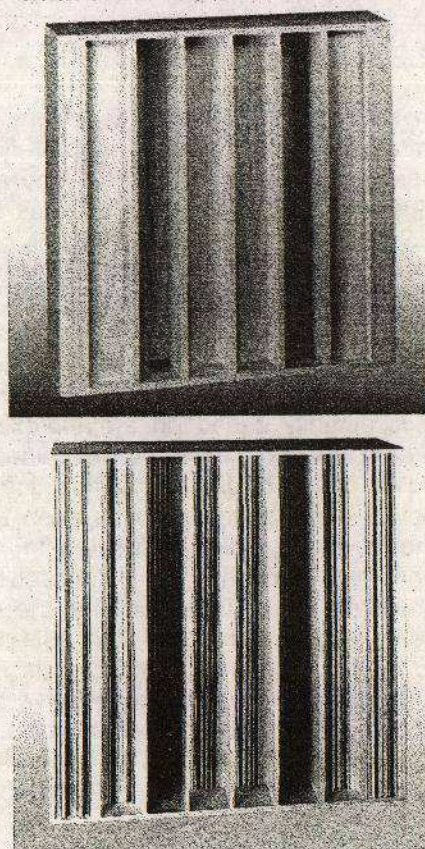


Figure 1 (Top) Schroeder QRD diffuser, (Bottom) RPG DiffRACTal.

* QRD and DiffRACTal are registered trademarks of RPG Diffusor Systems, Inc.

forward in the design of diffusers. For the first time, the acoustic performance of the surfaces was well defined. For example, if a quadratic residue sequence is used to determine the well depths, theoretically each diffraction lobe has the same scattered energy. Another important feature of the surfaces was that the design was relatively straightforward, governed by a small number of simple equations, and it was possible to produce approximate predictions of the scattering using very simple computer programs³. The appearance of the surface is fixed, the theory requires evenly spaced wells separated by fins for the surface to behave in the way Schroeder intended. Visually the surfaces present a rigid, regular structure and periodic geometric surfaces are common in interior design. But while for some the Schroeder surface represented a positive enhancement to the visual impact of a space, for others the appearance is unacceptable. If the surface fails to integrate into the architectural design, then essentially the control of the visual appearance of the space falls to the acoustician rather than the architect or interior designer, something clearly unacceptable to many. Consequently, a diffuser design technique is needed that not only enables the acoustic requirements to be met, but also enables flexibility in the looks of the device.

To a certain extent this can be achieved by increasing the palette of surfaces available. Since Schroeder's work, the design of diffusers has considerably advanced. Consequently, it is now possible to purchase a diverse range of manufactured surfaces with documented acoustics properties. Importantly, whereas in the past the performances of these surfaces were ill defined, it is now possible to measure, predict and characterise the scattering from such surfaces⁴.

2.2 Optimisation

In the mid-1990s a new technique was introduced into diffuser and reflector design - optimisation^{5,6}. Figure 2 illustrates the optimisation process for a Schroeder diffuser. Essentially the method leaves the computer to search for a well depth sequence that is better than the quadratic residue sequence. This can be achieved, because for all the elegance of the original Schroeder diffuser design, it is actually based on an approximate theory that is not always valid. During the development of diffuser optimisation, the power of the technique was seen to be the ability to make surfaces with more uniform scattering. Subsequently, however, it has turned out that the most useful aspect of the technique is its ability to enable arbitrary shaped objects to be designed. Diffusers no longer have to be constrained to the Schroeder profile. Provided a surface geometry can be represented by a small number of variables, and the scattering from the surface can be predicted, then optimisation can be applied. For example, it is possible to represent a simple curved surface by a Fourier series:

$$y = \sum_{n=1}^N [A_n \sin(nkx) + B_n \cos(nkx)] \quad (1)$$

Where x is the distance along the width of the diffuser, y the depth, k is a constant and A_n and B_n are shape variables.

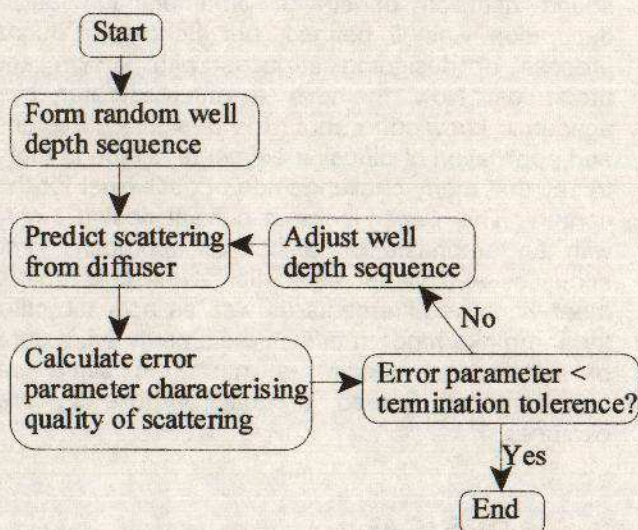


Figure 2 Optimisation of a Schroeder diffuser

By changing the shape variables the curved surface can be varied. Consequently, the computer can be sent to hunt for the best shape in a similar manner to looking for the best well depth sequence for a Schroeder diffuser. Figure 3 illustrates a surface produced by such a process. The curved surfaces have visual appeal to many; they are anyway a common feature in auditoria. It can be a less obvious acoustical treatment, and so will often blend into existing architectural designs. This technique has been used to design surfaces for a wide variety of sound production and reproduction rooms.

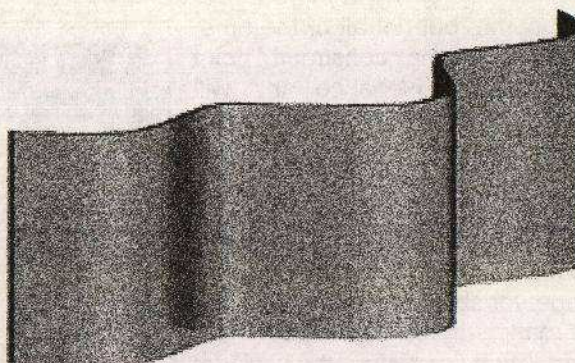


Figure 3 A curved surface formed from a Fourier series

Problems sometimes arise, however, when the best surface found by the computer does not meet the visual requirements of the architect. A curve was wanted, but the solutions produced were not quite what the designer originally envisaged. It is possible to constrain surfaces to try and force the shape to meet visual and physical constraints. This is done via a set of fuzzy coordinates through which the surface must pass. Figures 4A and 4B illustrate how such a system can be used to force a surface to pass through a particular point. The error parameter in the optimisation then becomes a sum of the diffusion coefficient that measures the scattering quality and a penalty value that measures how close to the constraints the surface is. This is often used to ensure that edges of

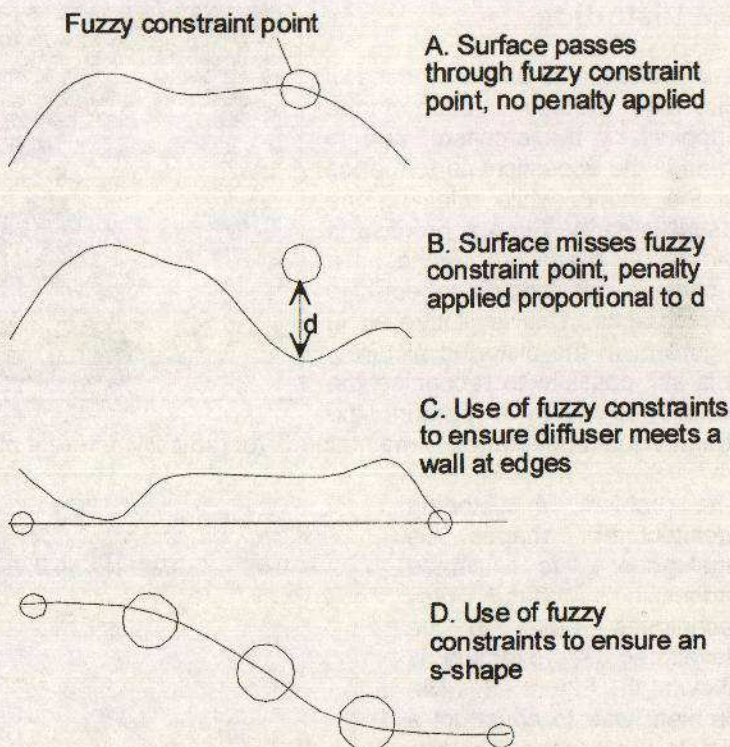


Figure 4 Use of fuzzy constraints to influence surface shape

diffusers meet walls as illustrated in Figure 4C. In addition, this technique can be used to ensure that: cusps are not formed between adjacent periods of periodic diffusers; the left and right edges of diffusers are at the same displacement so that periodic diffusers edges will meet without a discontinuity, and obstructions such as pillars are avoided. While using such a constraint system is straightforward for physical problems such as avoiding cusps, it is more problematic when trying to force the shape of the curve into the visual aesthetic demanded by the designer. Often during room design the interior designer has a definite idea about the general shape required for the diffuser - "we would like an s-shaped diffuser". Trying to come up with a suitable set of constraint points for this is possible, but involves some trial and error. For example, the points shown in Figure 4D will

work some, but not all of the time. In addition, the constraint point system lacks elegance and will slow down the optimisation process by increasing the complexity of the error function surface to be searched. It would be a much more superior system if the surface was designed from the shape variables in such a way that the only surfaces generated are ones that satisfy the visual constraints. The process devised to do this is distortion, as discussed below.

2.3 Distortion

It is proposed to use a process of distortion to take a base shape supplied by the architect, and to change the acoustical performance of the shape, while retaining the visual integrity. Such a process is familiar in image processing as a technique for adding effects to photographs. This is illustrated in Figure 5. In the distorted pictures, it is still possible to recognise the picture as being a person; the rough visual appearance is maintained, yet radically different pictures are obtained.

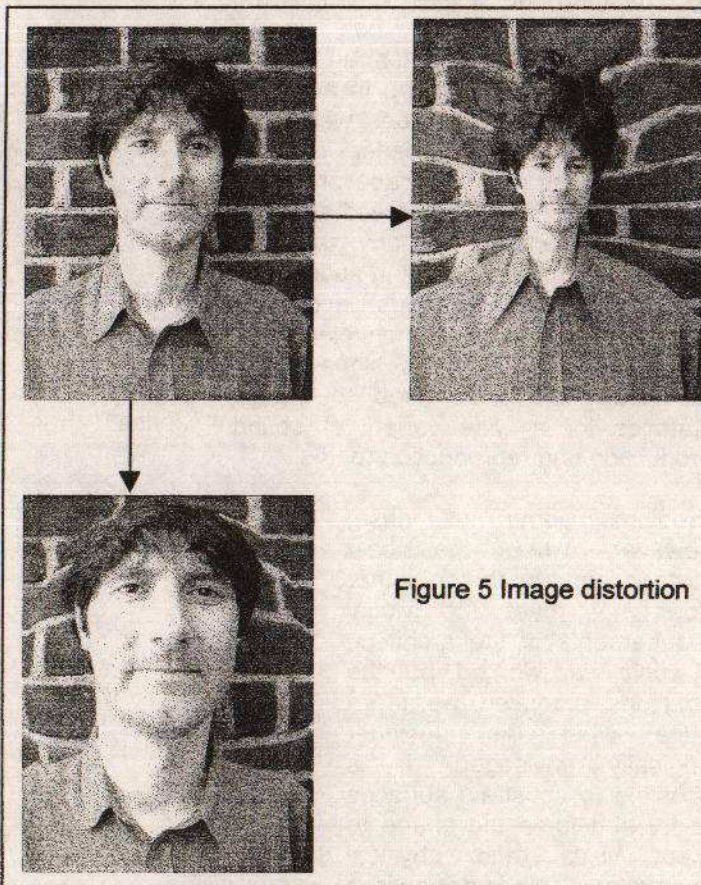


Figure 5 Image distortion

The problem of distorting architectural shapes is analogous to image processing, but new techniques have to be developed. An example is shown in Figure 6. The problem was to construct a simple arc surface. The two shapes shown represent two extremes that could be generated using the distortion process. The distortion process effectively stretched the shape vertically by pulling the apex up and down.

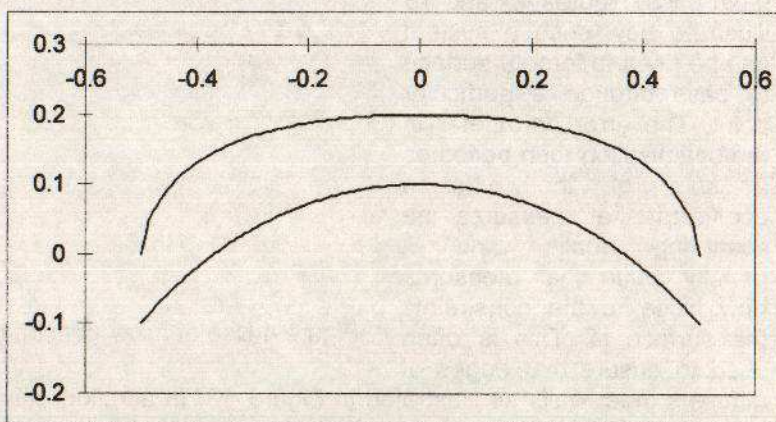


Figure 6 Examples of distorted arcs

Once re-scaling is done to ensure that the surface meets the required overall depth, this has the effect of producing different surfaces. In Figure 7, the polar distribution from the arc of a circle, a common architectural solution, and the optimised distorted arc are shown. The optimised surface produces the more even scattering showing that the design process worked. For more complex surfaces, different techniques are required based on modulation and compression concepts.

2.3 Periodicity

While it is possible to produce a single diffuser to cover a wide surface, it is much more common to use a base shape and repeat the pattern. Not only does this reduce manufacturing costs, a periodic look is often favoured. It seems that a periodic object enables the eye to more easily decode the design. A completely random surface, can be too difficult to interpret and hence not pleasing to the eye. (This is, of course, a bland generalisation, there are successful architectural designs where randomness is embraced, but it is more common for a periodic entity to be specified). Periodicity may be a problem acoustically. Periodic surfaces generate diffraction lobes, ideally these lobes should cover a wide angular range and be plentiful, so all directions get reasonable scattered energy, with no listeners receiving too low or too high a level. Unfortunately, as more periods are introduced into a device, the more narrow the diffraction lobes become, resulting in a reduction in diffusion. This is illustrated in Figure 8. There are many solutions to this problem. If a periodic structure is unavoidable, attempts should be made to extend the size of each period. The diffraction lobes from a periodic structure are governed by:

$$\sin(\theta) + \sin(\alpha) = \frac{m\lambda}{W} \quad m = 0, \pm 1, \dots, \pm n \quad n \leq \frac{W(1 + \sin(\alpha))}{\lambda} \quad (1)$$

Where θ is the diffraction lobe angle, α the angle of incidence, λ is the wavelength and W the repeat period. Equation (1) demonstrates that to gain more diffraction lobes at a given frequency, it is necessary to widen the diffuser period. (This also broadens the lobes, as the number of repeat units is smaller). Another technique to deal with lobe narrowing is to modulate the surface. Angus^{7,8} introduced this concept for use with Schroeder diffusers, but it can also be applied to other surfaces. The concept of the modulation is to use two base shapes, say arcs of two different sizes, and arrange them in pseudo random order on the wall. The mathematics of phase gratings means the pseudo random order is best determined by specialist sequences such as Barker codes. However, for most surfaces, a simple random arrangement may be used. Figure 9 shows the effect

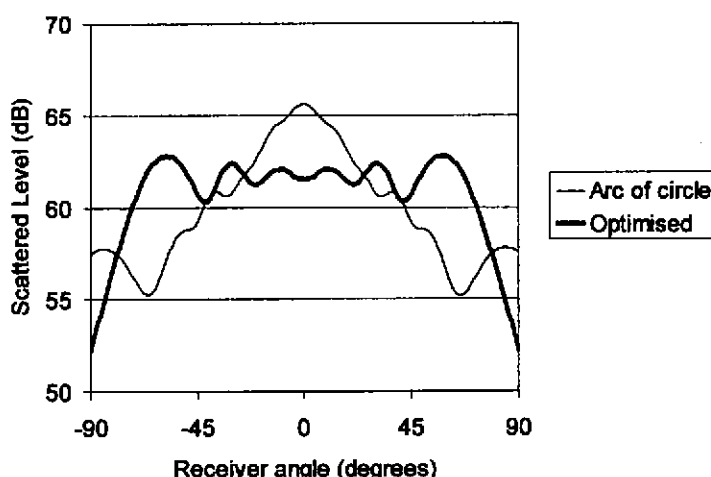


Figure 7 Scattered sound level for two surfaces at 2kHz.

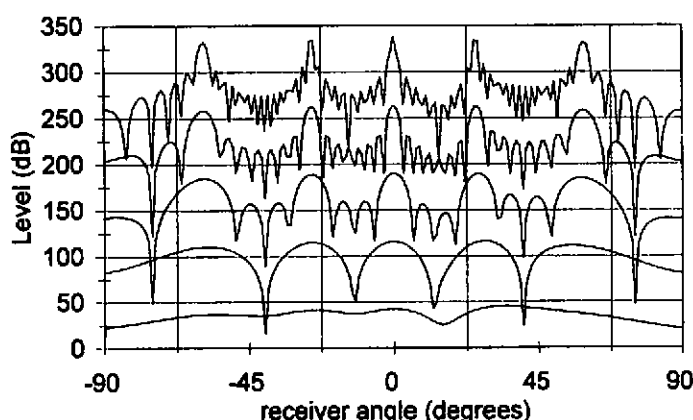


Figure 8 Scattering from a Schroeder diffuser for a different number of periods. (Top to bottom 16,8,4,2,1 periods). Lines displaced from each other vertically to aid clarity.

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of modulation, in this case for a Schroeder diffuser designed to produce a notch at 0°. In the periodic case, the two diffraction lobes at $\pm 40^\circ$ are clearly visible. Applying modulation removes these lobes. Similar results can be obtained for other base shapes designed to be uniform scatterers.

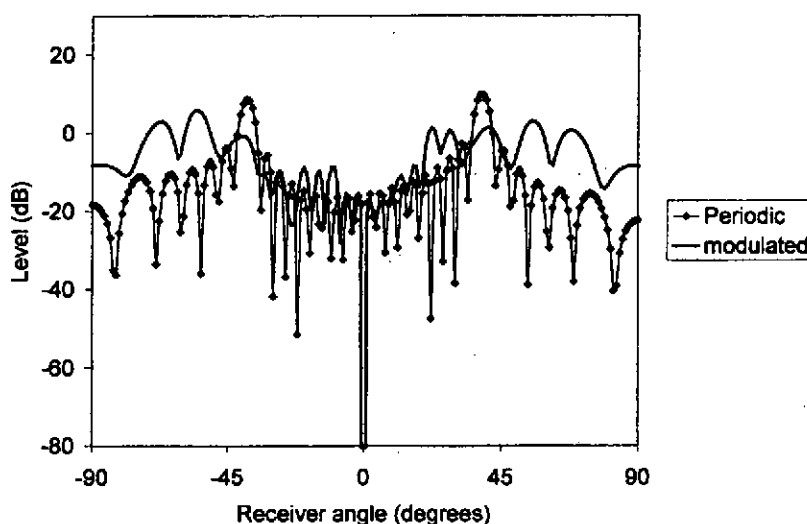


Figure 9 Scattering from a modified primitive root diffuser with and without modulation

3 CONCLUSIONS

This paper has outlined some old and some recent developments in diffuser design for auditoria. Discussions have centred on the belief that best practice in diffuser design requires not only consideration of acoustic performance, but also visual appearance. While not always the case, the most exacting design is usually required if the diffusers are to appear as a unified part of the architectural space. This has been achieved by increasing the palette of surfaces available to interior designers, beyond the rigid geometry of Schroeder diffusers. Furthermore, optimisation, including the use of distortion, enables a holistic approach to design. Common problems with periodic structures where there are contradictory visual and acoustic requirements have been discussed.

¹ Schroeder, M.R., "Binaural Dissimilarity and Optimum Ceilings for Concert Halls: More Lateral Sound Diffusion", *J. Acoust. Soc. Am.* **65**, 958-963 (1979).

² D'Antonio, P. & Konnert, J.H., "The QRD Diffractal: A New 1- or 2-Dimensional Fractal Sound Diffuser, 89th AES Convention, Preprint # 2938, Los Angeles (September 1990).

³ D'Antonio, P. & Konnert, J.H., "The Reflection Phase Grating Diffuser: Design Theory and Application", *J. Audio Eng. Soc.* **32**, No. 4, 228-238 (April 1984).

⁴ D'Antonio, P. and Cox, T.J., "Two Decades of Sound Diffuser Design and Development. Part 2: Prediction, Measurement and Characterisation", *J. Audio Eng. Soc.*, Vol. 46, Number 12, pp. 1075-1091 (December 1998)

⁵ Cox, T.J. "Optimization of profiled diffusers". *J. Acoust. Soc. Am.* **97**(5) 2928-2941 (1995)

⁶ T. J. Cox, "Designing Curved Diffusers for Performance Spaces", *J. Audio Eng. Soc.*, vol. 44, pp. 354-364 (May 1996)

⁷ Angus, J., "Large Area Diffusers using Modulated Phase Reflection Gratings", Presented at the 98th Audio Engineering Society Convention, Preprint 3954 (D4), (February 1995).

⁸ Angus, J.A.S. "Using Modulated Phase Reflection Gratings to Achieve Specific Diffusion Characteristics". Presented at the 99th Audio Engineering Society Convention, Preprint 4117, (October 1995).