ABSORPTION BY SURFACE DIFFUSERS

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1 SUMMARY

Diffusing surfaces are a contemporary design solution, which if used appropriately can enhance the acoustics of refurbished and newly built auditoria. In concert halls, the design specification for diffusers is for good dispersion with minimum absorption. Anecdotal evidence suggests, that there has been concern among practitioners that Schroeder diffusers can cause significant absorption. The literature contains contradictory data; some papers show Schroeder diffusers to be efficient absorbers, and others have measurements that show the absorption is small. The intention of this paper is to explain the contradictions in the literature. Prediction and measurement results will show what absorption can be expected from practical Schroeder diffusers. It will be shown that with careful design and proper construction absorption can be minimized. Alternatively, it is possible to turn these surfaces into efficient absorbers. Finally, an example of absorption for a non-Schroeder construction will also be given.

2 SCHROEDER DIFFUSERS

Schroeder diffusers[i,ii] consist of a series of wells of the same width but of different depth. Figure 1 shows typical examples. The different depth wells break up the reflected wavefront phase, and consequently cause the reflected sound to be dispersed. The ability of these surfaces to diffuse sound is well documented and so this aspect will not be discussed here. The focus of this paper is 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.

Figure 1. 1D (top) and 2D (bottom) Schroeder diffusers.

2.1 Construction Quality

Fujiwara and Miyajima[iii] showed random incidence absorption coefficients ranging from 0.3 to 1 for two dimensional quadratic residue diffusers. Commins, Auletta and Suner [iv] measured random incidence absorption coefficients peaking at about 0.5 for a Schroeder diffuser. These high absorption coefficients are in marked contrast to random incidence absorption coefficients measured on commercial samples. Examples of these measurements are shown in Figure 2 where the average absorption coefficient is 0.1 - 0.2 depending on the construction.

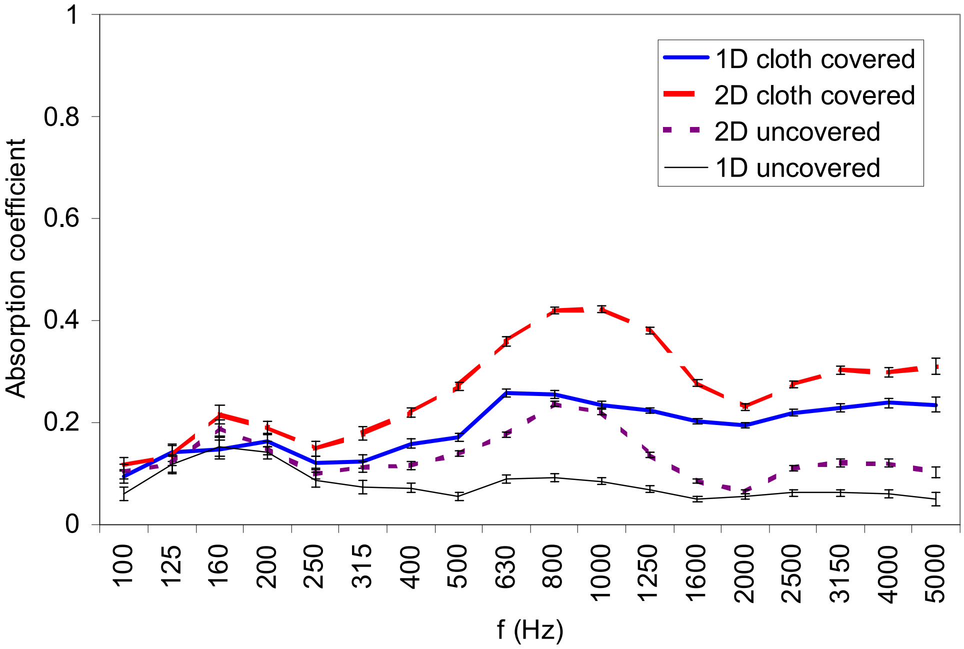

Figure 2. Random incidence absorption coefficient for the 1D and 2D Schroeder diffusers shown in Figure 1. Results shown for with and without cloth covering at the well entrances.

The contradiction between the measurements in Figure 2 and references 3 and 4 can probably be explained by construction quality. Fujiwara[v] later publication showed that the excessive absorption seen in reference 3 was caused by poor construction. At low frequency, slits formed at the bottom of the wells were the cause. These slits opened up to cavities at the back of the diffuser, forming rather efficient microperforated Helmholtz absorbers at the bottom of the wells. These Helmholtz absorbers caused the excess bass absorption below the design frequency. (Fujiwara, Nakai and Torihara [vi], and Wu, Cox and Lam[vii] have since gone on to exploit this mechnaism by intentionally adding Helmholtz resonators to these surfaces to form efficient absorbers). Poor construction can also lead to connections and acoustic coupling between the wells[v]. This coupling can also lead to additional absorption at specific frequencies and angles of incidence. With this coupling, the surface now forms an extended reaction surface and the excess absorption is hard to predict. Indeed, the coupling could result in a decrease in absorption for some frequencies and angles of incidence. As well as affecting the absorption of the diffusers, the poor construction will affect the diffusion generated. The impedance of the wells will be changed, and so will the scattered polar response. Consequently, proper sealing of slits and cracks in the diffuser is necessary both to obtain low absorption and defined diffusion.

2.2 Surface roughness

Surface roughness is also important to the absorption of diffusers; this is especially true for Schroeder diffusers because of the primary absorption mechanisms in these devices. Schroeder diffusers absorb mainly because of: (i) high energy flows from wells in resonance to wells out of resonance, and (ii) ¼ wave resonant absorption in the wells. If the surfaces of the Schroeder diffuser are rough, then the absorption at the walls of the wells increases due to additional frictional losses. Figure 3 illustrates the effect of boundary layer absorption with a concrete Schroeder diffuser. When the surface is unfinished, the concrete surface is porous and rough and so absorption at the boundaries is high. This results in excess random incidence absorption being measured at mid to high frequencies. If the surface is painted, the concrete is smoother and no longer porous; consequently the boundary absorption is reduced. Fujiwara[v] produced a similar finding. He compared the attenuation constant for plywood and aluminium wells, and showed the smoother aluminium was less absorbing.

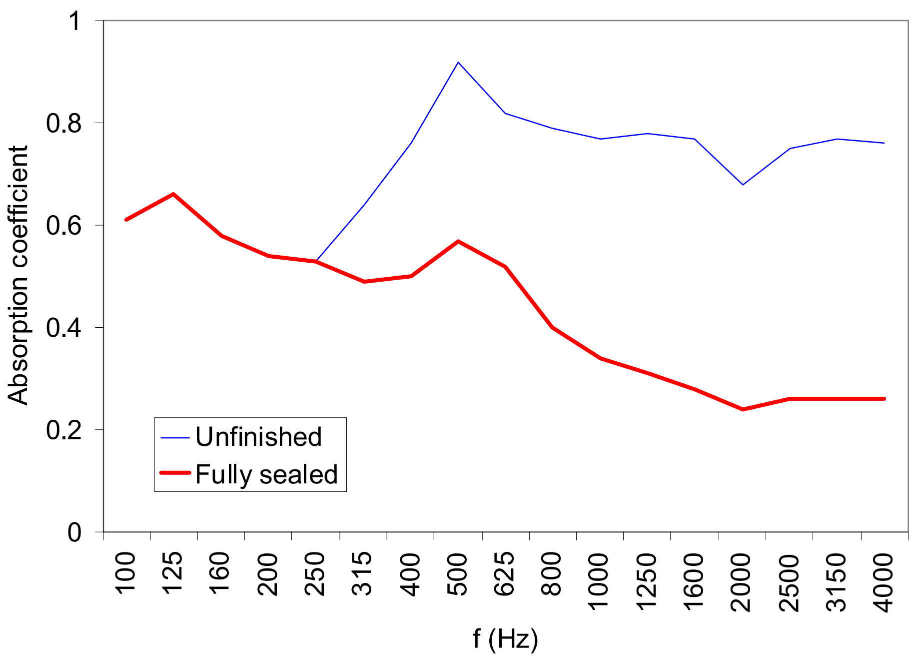

Figure 3. Random incidence absorption coefficient for a concrete Schroeder diffuser illustrating the importance of sealing surfaces and surface roughness.

2.3 Covering

Cloth wrapping diffusers is a common method for hiding the appearance of surface modulation if a designer feels that the diffuser should be heard but not seen. This is not to be recommended for Schroeder diffusers, however, due to the absorption mechanisms inherent in the construction. (Unless additional absorption is desirable for reverberation control.) To understand why covering is not recommended, it is necessary to describe the primary absorption mechanisms inherent in these devices.

Even when the Schroeder diffuser is well constructed, with no slits, smooth sides and well sealed with paint or varnish, the absorption is greater than one would expect from a series of quarter wave resonators. Kuttruff[viii] and Mechel[ix] postulated that the excess absorption was caused by flow between the wells. Consider a Schroeder diffuser irradiated by a single frequency acoustic wave. The acoustic energy within each well will be different. Wells which are in resonance will have high energy, wells which are not resonating will have low energy. This will lead to an uneven energy distribution across the front face of the diffuser. Energy will flow from high energy wells to low energy wells as nature will try to even out the distribution of energy. This process generates high particle velocity at the well entrances as energy flows between wells. Fujiwara, Nakai and Torihara[vi] have produced visualisations of this using the Kundt's method, showing that the particle velocity is up to fourteen times greater at the well entrances compared to the incident wave alone. Wu, Cox and Lam[x] demonstrated that this energy flow is the cause of the excess absorption in Schroeder diffusers through a series of impedance tube measurements and Fourier Theory predictions.

Cloth wrapping a Schroeder diffuser places resistive material at the entrances of the wells where the particle velocity is high. Consequently, excess absorption will occur. Figure 2 shows that cloth wrapping Schroeder diffusers approximately doubles the absorption generated for both 1D and 2D surfaces. The cloth in this case is typical seat swap covering material. For concert halls, where absorption usually needs to be minimised, cloth wrapping of Schroeder diffusers should be avoided. Where cloth wrapping is unavoidable, the material should be placed as far away from the surface as possible, say a minimum of one well width in distance, and the material should have the lowest flow resistivity possible.

2.4 Design

Figure 2 shows the difference in absorption for 1D and 2D quadratic residue diffusers; the surfaces were shown in Figure 1. The 2D surface has greater absorption. The reason for this is probably two fold:

1. There are a greater number of well depths in the 2D diffuser compared to the 1D surface. The 1D diffuser only has four unique well depths, whereas the 2D surface has six different well depths. This means that there are more quarter wave resonances in the 2D surface, leading to more frequencies at which resonance is occurring. This means that the absorption due to quarter wave resonance is significant for more frequencies, and the energy flow between the wells is greater leading to more losses from that mechanism.

2. There is a greater surface area of well boundaries in the 2D diffuser compared to the 1D surface. It is at these boundaries that viscous boundary layer losses occur. Consequently, it is expected that the greater the boundary area, the greater the absorption.

Commins, Auletta and Suner[iv] experimentally investigated the effect of sloping the bottom of the diffuser wells. Their results showed that the absorption could be reduced. The absorption from the diffusers with non-sloping well bottoms seemed rather large, so whether the decrease in absorption is due to the slopes or maybe some change in construction quality is not known. The effect of the slope would be to broaden the resonances of the wells. This might decrease the energy flow within and between wells at resonance and so reduce the absorption. The drop in absorption, however, looks rather large for this to be the only effect. This technique would affect the diffusion produced at mid to high frequencies, and this would have to be allowed for at the design stage.

When a Schroeder diffuser is designed, the high frequency limit comes from the well width. If the wavelength becomes too small, then plane wave propagation breaks down and the diffuser no longer follows simple design equations. Despite this the diffuser will still continue to diffuse, just in a less controlled fashion. The low frequency limit for diffusion comes from the well depth or for narrow diffusers the period width. The low and high frequency bandwidth equations indicate that the best diffuser is one where the well width is narrow, the prime number generator is large and the well depth is deep. Very narrow deep wells are not often used, however, because of cost and absorption. Practical diffusers are usually made with

Figure 4. A diffuser using a fractal construct to reduce absorption from extended bandwidth devices.

well widths greater than 2.5cm to minimise absorption due to viscous boundary layer absorption at the well sides, and widths of about 5cm are common. One solution for obtaining good bandwidth while avoiding very narrow deep wells, is to use a fractal design. An example of this is shown in Figure 4. The diffuser is essentially a two-way diffuser, with smaller diffusers mounted within a larger diffuser each designed to disperse different frequency ranges. This removes the need to use narrow and deep wells.

2.5 Designing for absorption, design for diffusion

It is also possible to construct Schroeder surfaces to maximise the absorption and make rather efficient absorbers. These can then form fibreless washable absorbers if the covering is made of wire mesh rather than cloth, but they are rather expensive to make. Figure 5 shows the absorption

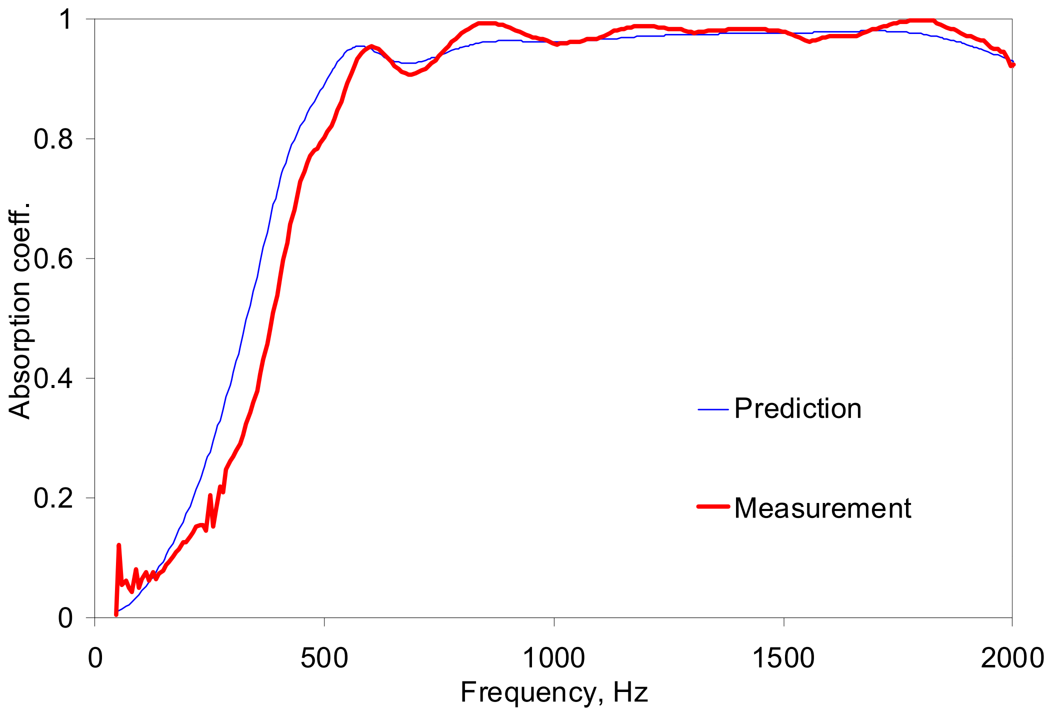

Figure 5. Normal incidence absorption coefficient measured in an impedance tube and predicted using a Fourier model, for a Schroeder-style surface designed for maximum absorption. Data from vii.

from a surface which has been optimised to maximise the absorption. Although the surface used to produce the results in Figure 5 has the same ancestry as those in Figure 1, crucial design differences result in radically different absorption properties. The two different design remits are contrasted in Table 1.

Table 1. Construction differences between Schroeder diffusers and absorbers

	Schroeder surface for absorption	Schroeder surface for diffusion (minimal absorption)
Well width	Usually narrow to exploit viscous boundary layer losses.	Usually >2.5cm to minimise boundary layer losses.
Covering	Key to good absorption. Covering should be chosen so surface resistance is $\approx\rho_0 c$ to maximise absorption.	Should not be covered. If covering unavoidable, use low flow resistivity material away from well entrances.
1D vs 2D	2D surface gives more absorption.	2D surface gives hemispherical dispersion, 1D surfaces diffuse in a single plane.
Number of different depth wells	Determined by the need to have a sufficient number of quarter wave resonances in absorption bandwidth.	A larger N usually makes a better diffuser.
Depth sequence	Well depths should be chosen to evenly distribute well resonances across absorption bandwidth, best done using numerical optimisation.	Chosen to maximise dispersion, best done using numerical optimisation.
Deepest well depth	Determines low frequency limit of absorption.	Determines low frequency limit of diffusion, except when period width is small.
Construction	Well sealed, no slits	Well sealed, no slits
Well sides	Can be rough	Should be smooth

3 NON-WELLED DIFFUSERS

Schroeder diffusers consist of a series of resonators, and the resonances are directly and indirectly responsible for any excess absorption. It makes sense, therefore, to remove the resonance structures and therefore reduce absorption. Furthermore, Schroeder diffusers do not have a monopoly on good diffusion; they just happen to be one of the few surfaces where the design can be carried out relatively simply. Using numerical optimisation, it is possible to design surfaces based on arbitrary shapes[xi,xii], furthermore, the scattering is more even than classical Schroeder diffusers.

There will still be some absorption, whatever the diffuser shape. A rough surface creates evanescent waves which represent energy propagating around the surface but not into the far field. This reactive energy will generate a particle velocity profile, which will lead to additional boundary layer absorption when compared to a flat surface. The particle velocity profile will have a smaller amplitude when compared to the case of a Schroeder diffuser, and so absorption should be less.

A diffuser was constructed from a periodic array of arcs. The surface modulation was 0.14m deep, and the repeat length was about 0.6m. The surface was made from a 3mm gypsum. These arcs were measured in a small reverberation chamber following ISO 354. Figure 6 shows the measured absorption coefficient, which averages about 0.1 across the key design frequencies. Consequently, the sound attenuation on the first reflection from these surfaces is 0.5dB.

4 CONCLUSIONS

The causes of absorption generated by Schroeder diffusers have been reviewed. Some previously published absorption coefficients have been very high either due to poor construction, or because the authors were attempting to make absorbers from these surfaces. The requirements for ensuring minimal losses when making

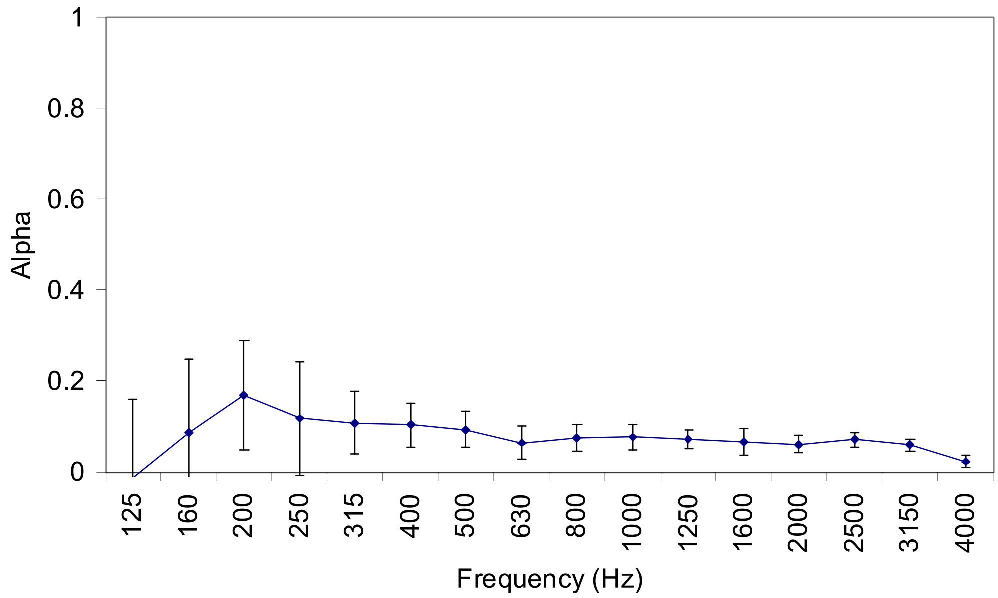

Figure 6. The random incidence absorption coefficient for an optimised curved diffuser.

Schroeder diffusers have been outlined. These requirements have been contrasted with constructions designed to maximise absorption. With proper design, the absorption of Schroeder style diffusers should not prevent their use in concert halls, however, other considerations, such as visual appearance and cost can make other shapes more attractive to designers. Curved optimised diffusers not only have inherently low absorption, but they also have better diffusion performance than Schroeder diffusers.

5 REFERENCES

[i] M. R. Schroeder, "Diffuse sound reflection by maximum-length sequences," J.Acoust.Soc.Am. 57(1), 149-150, (1975).
[ii] M. R. Schroeder, "Binaural dissimilarity and optimum ceilings for concert halls: more lateral sound diffusion", J.Acoust.Soc.Am. 65, 958-963 (1979).
[iii] 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).
[iv] D. E. Commins, N. Auletta, B. Suner, "Diffusion and absorption of quadratic residue diffusers," Proc.I.O.A. 10(2), 223-232, (1988).
[v] K. Fujiwara, "A study on the sound absorption of a quadratic-residue type diffuser," Acustica, 81 370-378. (1992).
[vi] K.Fujiwara, K.Nakai and H.Torihara, "Visualisation of the sound field around a Schroeder diffuser", Appl. Acoust. 60(2) 225-236. (2000)
[vii] Tao Wu, Trevor J. Cox, and Y. W. Lam, "A profiled structure with improved low frequency absorption," J.Acoust.Soc.Am. 110, 3064-3070, (2001).
[viii] H. Kuttruff, "Sound absorption by preudostochastic diffusers (Schroeder diffusers)", Appl. Acoust. 42, 215-231 (1994).
[ix] F.P.Mechel, "The wide-angle diffuser - A wide-angle absorber?", Acustica, 81, 379-401 (1995).
[x] T.Wu, T.J.Cox and Y.W.Lam, "From a profiled diffuser to an optimised absorber", J. Acoust. Soc. Am. 108 (2), 643-650 (2000).
[xi] T. J. Cox, "Optimization of profiled diffusers," J.Acoust.Soc.Am. 97(5) 2928-2941 (1995),
[xii] T. J. Cox, "Designing curved diffusers for performance spaces," J.Audio.Eng.Soc. 44. 354-364. (1996).