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CONTRASTING DIFFUSERS

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1. INTRODUCTION

In recent decades, many innovative diffuser designs have been produced and applied in a wide variety of reproduced sound applications. Diffusers have been formed from a wide variety of rough surfaces and by varying the surface impedance. This paper will discuss methods for generating diffuse reflections, highlighting the acoustic, and non-acoustic pros and cons.

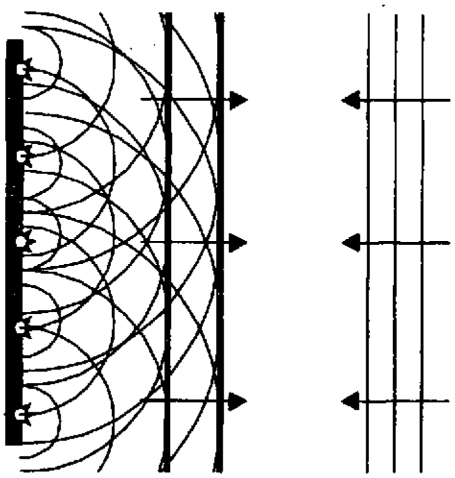
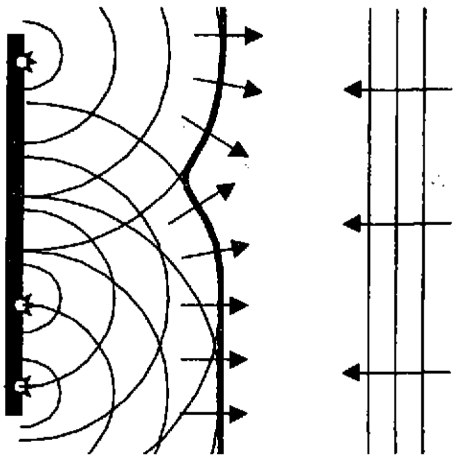


Figure 1. Scattering using Huygen's principle. (a) Above, large plane surface, (b) below using absorption to alter reflected wavefront.



2. DIFFUSION MECHANISMS

In the context of surface scattering, diffusion is the process whereby a surface breaks up an incident wavefront, so causing reflecting energy to propagate in all directions. The reflected wavefront can be explained by following Huygen's principle. A series of imaginary secondary sources are placed on the surface. It is the interference between waves from the secondary sources that form the reflected wavefront. For a plane surface, much larger than a wavelength in size, no diffusion occurs as shown in Figure 1a. Diffusion is created by altering the imaginary secondary sources. For example, by applying absorption in patches, some of the secondary sources will be missing and this will also result in a breaking up of the wavefront and diffusion as shown in Figure 1b. The use of absorbent patches to generate diffusion is used in Binary Amplitude Diffusers[1]. This is an example of creating diffusion by changing the impedance of a surface.

Another example of this is a Schroeder diffuser[2]. In this case it is the radiating phase rather than amplitude of the imaginary sources at the well openings that are altered to produce diffusion (the radiating phases being determined by the well depths). The other mechanism for producing diffusion is surface roughness. By altering the position of the secondary sources, as happens with curved diffusers for example, it is possible to alter the reflected wavefront. (Although as the surface becomes more rough, Huygen's becomes a less useful construct due to mutual interactions between the imaginary sources on the surface).

3. PREDICTION, MEASUREMENT, EVALUATION

To enable the relative performance of the diffusers to be compared, it is necessary to have systems to accurately measure and predict the reflections from surfaces. This work draws on maximum length sequences systems for measurement[3] and Boundary Element Methods (BEMs) for prediction[4,5]. These techniques have been shown to be accurate methods for obtaining the scattered polar distribution. While it is possible to evaluate the quality of diffusion from the polar distributions, when a large number of source positions, frequencies and surfaces are to be considered, it is more efficient to use a diffusion coefficient. The diffusion coefficient is a single figure of merit characterising the quality of diffusion, in a similar way to the absorption coefficient measures the degree of absorption. A diffusion coefficient of zero indicates all the energy is scattered in one direction, a value of one represents complete diffusion with the energy uniformly reflected into all directions in a semicircle in 2D, or hemisphere in 3D[6].

4. SURFACE ROUGHNESS

To alter the Interference patterns between the waves from secondary sources using surface roughness, it is necessary to move the secondary sources by a distance significant compared to wavelength. Consequently, for wide surfaces, the depth of the diffuser determines the low frequency limit of the diffusion. In Figure 2, the diffusion from an optimised curved hard surface[7] (Opticurve) along with the diffusion from a plane surface of the same size (Plane hard) is shown. The surface roughness of the Opticurve produces significantly more diffusion than the plane surface

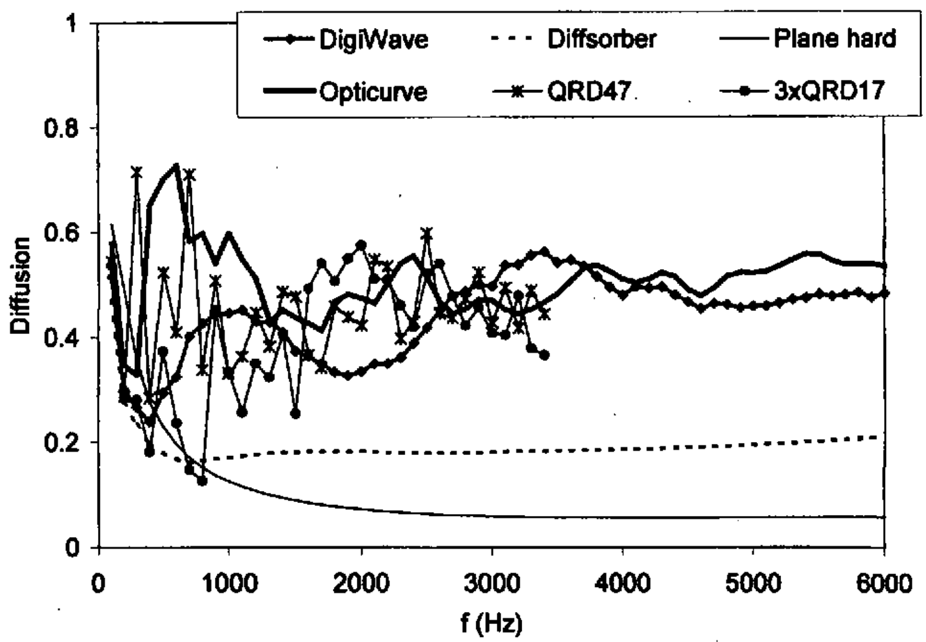


Figure 2 Diffusion from various surfaces.

above ≈350Hz, or when the depth is ≈λ/3. This limitation of requiring surfaces to be deep compared to wavelength, is one of the major drawbacks of using surface roughness for diffusion. Very deep surfaces are usually more expensive to make and take up valuable space, particularly in small rooms. Furthermore, any rough surface will have some absorption associated with it due to viscous boundary effects and energy flow across the surface. As the surface becomes deeper this absorption will increase without careful design.

In some applications the appearance of rough diffusers is unacceptable to architects. Unsurprisingly, it is usual for the architect to impose a visual style on a space, rather than the form of a room to be determined by the acoustic function[8]. Consequently diffusers have to blend with the visual scheme devised by the architect, and this can be done by having a range of surfaces on offer (Schroeder, stepped, curved etc). Another solution, covering diffusers with acoustical transparent material, should be addressed with caution. High particle velocities near the surface are present as acoustic energy flows to equalise pressure differences across the rough surface. Consequently, covering the diffuser with a cloth, a resistive layer, may result in excess absorption. This absorption is of practical concern for structures with well defined resonances, for example with Schroeder diffusers. (This problem may be reduced, however, if the cloth is spaced a sufficient distance from the diffuser). In fact Schroeder diffusers can be made into reasonable absorbers by reducing the well widths and placing a cloth over the well entrance[9]. If optimisation is used to choose the well depth sequence, instead of using depth sequences determined for diffusing reasons, a very useful absorber is produced[10].

A further visual acoustic conflict can arise with periodicity. It is normal to manufacture narrow diffusers, and then cover a large area with many periods of this one base shape. There are two advantages, first in reducing the manufacturing cost, especially if moulding technologies are being used, and second in producing a visually appealing surface. When superficially viewing the surface, it is possible to decode that there is a periodic arrangement and so the surface is easy to understand. On further inspection the details of the base shape can be investigated, and so the surface has interest when examined for longer. Completely random shapes are rarely exploited visually in architecture, presumably because they can be difficult for the brain to interpret unless some underlying structure can be found - and underlying structure implies a non-random shape. Periodic arrangements, however, are not always desirable for acoustic reasons. For many practical arrangements, the scattering from the surface has much more to do with the effects of the periodicity, than with the shape of the individual diffuser unit. This is demonstrated in Figure 3

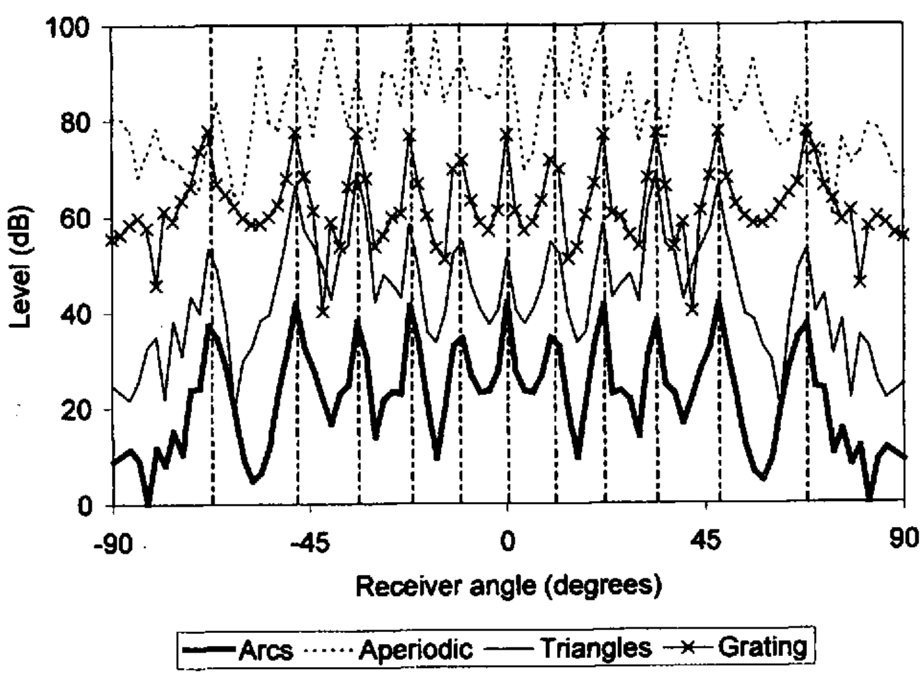


Figure 3 Polar response for three surfaces and a diffraction grating. 1500Hz. Polar responses displaced vertically for clarity. Vertical marks give the diffraction lobe directions for periodic case.

where the scattering from a periodic set of arcs and triangles are shown. In addition, the radiation from a simple array of sources, equivalent to a diffraction grating, is shown. The sources in the array are spaced apart by the repeat distance of the periodic surfaces. The dominance of the grating pattern in the scattering for both the periodic arcs and triangles can be seen. Consequently, the variations in the polar distributions when altering the base shapes in this frequency range are relatively small. A further consideration is that with periodic diffusers the low frequency cut-off of the diffusion is often not determined by the surface depth, but by the repeat distance i.e. the width of one period. Therefore generating better diffusion requires treatment of the periodic arrangement by increasing the repeat unit length. This can be done by making the diffusers physically wider, or by breaking up the regularity of the surface by modulation[11]. An example of modulation is where two different base shapes are used which are arranged in a pseudo-random order on the wall. There is no longer periodicity in the wall structure and so the regular lobes are removed. Furthermore, this also means that the low frequency limit of diffusion is more likely to be determined by the depth of the diffuser and not the repeat distance. Figure 3 shows the scattering from an aperiodic arrangement of a simple base shape demonstrating the removal of the regularity of the lobes when compared to the other periodic structures and the grating in the same figure.

Figure 4 illustrates this in terms of diffusion. *Periodic W=2A* is a periodic geometric shaped diffuser; *periodic W=A* is the same shape with the same depth but half the width in each base unit; *modulated* is a pseudo-random arrangement of these two base shapes, and *plane* is a plane panel for comparison. By doubling the repeat unit length, going from W=A to W=2A, the lower cut-off of the diffusion has dropped one octave, showing that for W=A the lower cut-off frequency was determined by the base shape width and not the depth. In addition, going from W=A to W=2A increases the diffusion for nearly all frequencies because the number of diffraction lobes is approximately doubled, smoothing the polar distribution. The ability for modulation to improve on

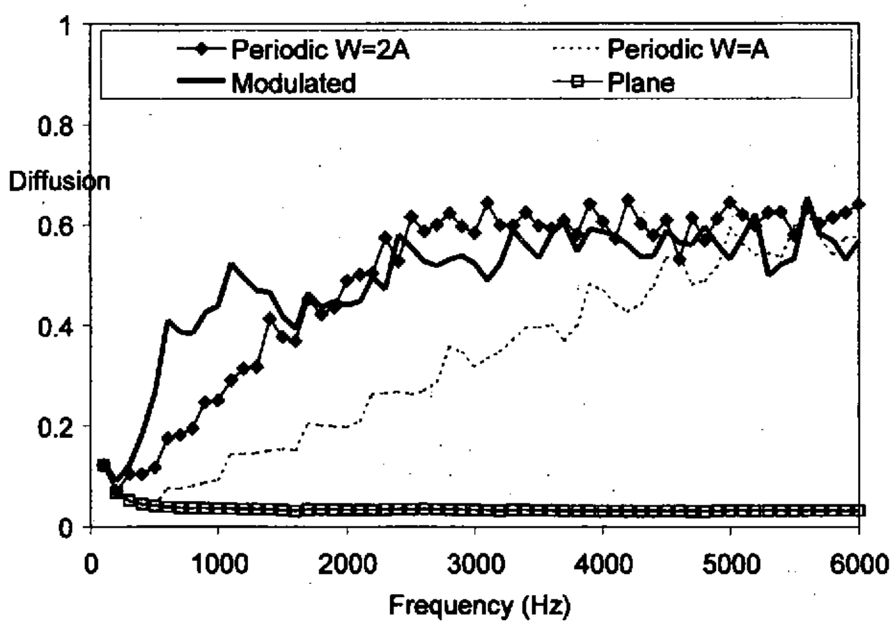


Figure 4 Effects of periodicity and repeat unit length on diffusion.

periodic arrangements is again demonstrated, although this is the first published evidence that for typical diffuser sizes the improvement is limited to low and mid frequencies. Unfortunately, modulation also removes the visual regularity that is often appealing. As will be shown later, generating visual periodicity along with acoustic aperiodicity is easier with a variable impedance surface.

5. VARIABLE IMPEDANCE

The source strength of the secondary sources can be altered by the use of absorptive material. This then alters the reflected wavefront. In fact, a block of absorbent alone makes a very efficient diffuser, although this is not very useful as the pure absorbent reflects negligible energy in any direction. This is shown in Figure 5 where the scattering from a variety of surfaces includes the scattering from a planar piece of 1" absorbent. A more useful device is formed by covering the absorbent with a hard material containing holes, such a mask is shown in Figure 6. This then forms a grid of hard and soft areas with the potential to cause diffusion due to the changing impedance across the front face. The surface is a hybrid, a diffuser that is partly absorbing, a diffsorber. Figure 5 illustrates the scattering from a diffsorber and Figure 2 showed the diffusion spectrum. Improved

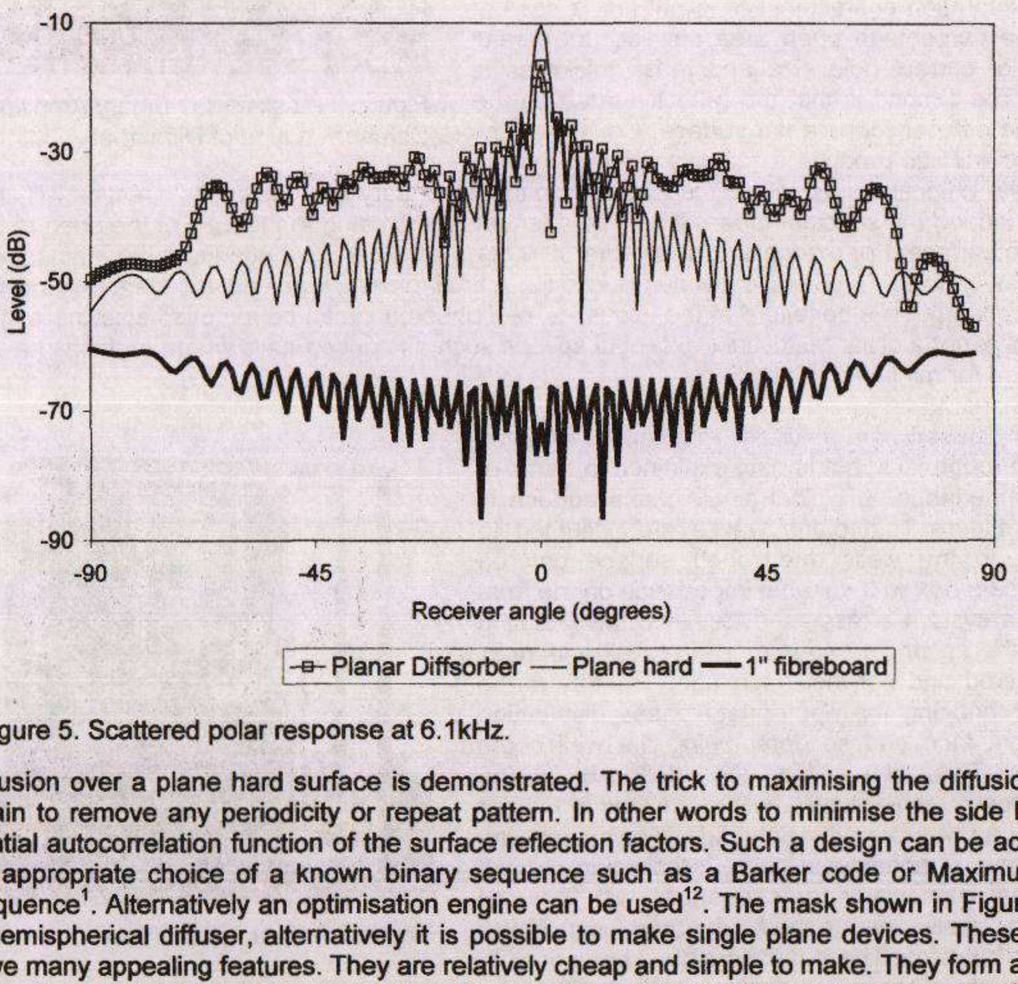


Figure 5. Scattered polar response at 6.1kHz.

diffusion over a plane hard surface is demonstrated. The trick to maximising the diffusion is once again to remove any periodicity or repeat pattern. In other words to minimise the side lobes of a spatial autocorrelation function of the surface reflection factors. Such a design can be achieved by an appropriate choice of a known binary sequence such as a Barker code or Maximum Length Sequence[1]. Alternatively an optimisation engine can be used[12]. The mask shown in Figure 6 forms a hemispherical diffuser, alternatively it is possible to make single plane devices. These surfaces have many appealing features. They are relatively cheap and simple to make. They form a relatively flat surface, which has great appeal to architects who wish their diffusers to be heard and not seen. An aperiodic arrangement can be made to reduce periodicity effects without having to impose an aperiodic visual appearance, as was the case with rough surfaces. These diffusers enable designers to have a surface that has both appealing absorption and diffusion properties. In small rooms with extremes of absorption and diffusion, the sweat spot of good acoustics is relatively small and centred around the sound engineer and the desk. Unfortunately, this can mean that others elsewhere in the room don't get good listening conditions. A diffsorber enables the acoustics across a small room to be more uniform, and the listening conditions to be better for a larger number of people. Finally, the surfaces are relatively thin. The diffuser in Figure 2 starts diffusing at about 1000 Hz, about 2-3 octaves below what might be expected from a simple $\lambda/2$ calculation.

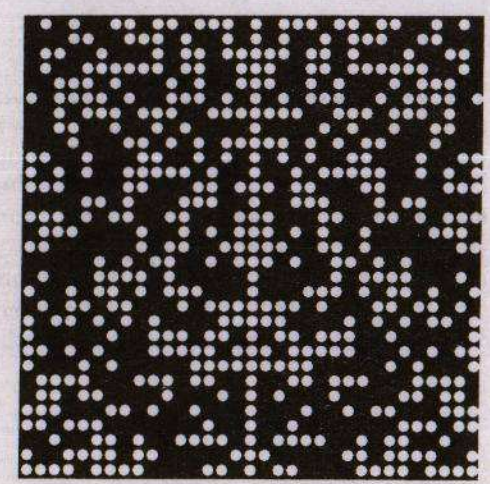


Figure 6 Mask for 2D Binary Amplitude Diffuser - a type of Diffsorber

These devices, however, have a couple of drawbacks. First, the simple construction provides more absorption than might be imagined. The incident wave at low to medium frequencies "sees" more absorbent than might be expected by calculating just the open to total area. This is due to resonant behaviour due to a finite thickness of absorbent in front of a hard surface, and the mass effect of the air in the holes. Achieving the desired absorption characteristics is not just a case of getting the percentage open area correct, but careful selection of correct hole size and mask thickness is required. The second is that the reflective area on the front of the diffuser forms a flat surface. Consequently, this device will still produce a major scattering lobe in the specular reflection direction as the waves from the secondary sources in this direction will all be in phase. Indeed the specular lobe will only be attenuated according to the ratio of the open to total area in the surface. For example, a mask with 50% open area can only attenuate the main lobe by 6dB. A solution to this problem is given in Section 6. A final remark, these diffusers are only useful if additional absorption is beneficial to the acoustics, or if absorption can be removed elsewhere in the room. This is not a great restriction, except in spaces such as concert halls where surfaces have to be designed for minimum absorption.

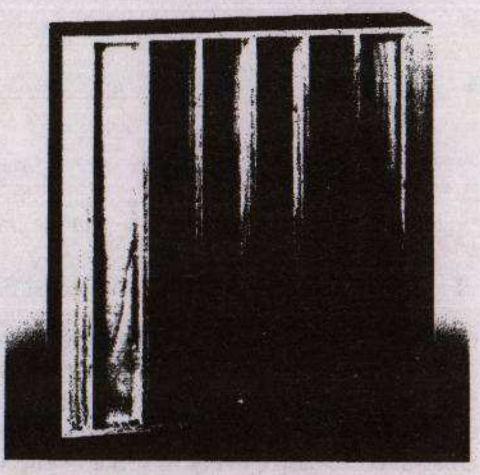


Figure 7 A Schroeder diffuser

Schroeder diffusers[2] are a surface that causes diffusion by surface roughness, but is best explained in terms of variable impedance. A typical single plane surface is shown in Figure 7. If plane waves are assumed to propagate in the wells, the rough surface can be modelled as a box with variable impedance on the front face. If the system is assumed lossless, the radiating phase of the secondary sources at the well entrances will be altered and not the magnitude. The key to the design is choosing the appropriate phase distribution on the front face and so determining the well depth sequence. This can either be done by using mathematical sequences with desired Fourier properties, as was done by Schroeder[2], or by applying optimisation techniques[13]. Optimisation has advantages, particularly for sequences with a small number of wells per period, in producing better broadband diffusion. These diffusers have been used in a wide variety of spaces world wide, but the form does lead to problems. Poor design and construction can lead to excess absorption and more importantly, it is a shape that has a distinctive appearance which some find unappealing. The performances of two QRDs are shown in Figure 2, and will be discussed in Section 7.0.

6. ROUGHNESS AND VARIABLE IMPEDANCE

By bending the front of a Diffsorber, a combination of both variable impedance and surface roughness is used to generate diffusion[12]. As two mechanisms are involved in reducing the specular reflection, the problems associated with planar diffsorbers discussed above are reduced. The diffusion from such a device is shown in Figure 2 (Digiwave). A clear improvement on the planar diffsorber is demonstrated. Furthermore, the roughness of the diffuser can be made periodic, so maintain visual periodicity, while the pattern of absorption and reflection patches can be made random so preserving acoustic aperiodicity.

7. DISCUSSION

It is interesting to contrast different types of diffusers: planar diffsorber; hard curved (Opticurve); curved diffsorber (Digiwave), and two QRDs (QRD47) and (3xQRD17) which are based on N=47 and N=17 respectively. This discussion will concentrate purely on the diffusion performance shown in Figure 2 as other acoustic and non-acoustic considerations have already been discussed. The planar diffsorber is of most use where moderate diffusion is required. For the most critical applications, some form of surface roughness needs to be used to reduce the coherence of the waves from the secondary sources in the specular direction. The performance of the Digiwave, while worse than the Opticurve, is remarkably good. This surface is shallow, but by using absorption significant diffusion is generated at 1-2 octaves lower than expected. This is because the absorption layer has a greater effect on the incident wave than a similar sized layer of air. The Opticurve produces the best diffusion over the widest bandwidth, outperforming both the Schroeder diffusers and the diffsorbers. Schroeder diffusers are locked into a specific geometry, within which lie the diffusers' strengths and weaknesses. Optimisation, as used in the Opticurve, enables the surface shape to be less constrained, and so enabling better diffusion. Figure 8 shows a photograph of a studio illustrating the development of diffusers in recent decades. The rear wall uses a fractal design, with direct reference back to Schroeder's pioneering work. The fractal diffuser imbeds smaller diffusers within a larger diffuser to provide broadband diffusion. Significantly, this is an extremely deep diffuser, and this use of a fractal design has great advantages in reducing the excess absorption that might occur if a single Schroeder diffuser was designed to operate over such a wide bandwidth. The side walls and ceiling use the curved diffsorbors, a development of more recent years, to provide a mixture of absorption and diffusion, and on the side walls to provide significant diffusion from a limited depth.

8. CONCLUSIONS

Diffusion can be generated by two mechanisms: variable impedance and surface roughness. Planar diffsorbers, which are diffusing and partly absorbing, generate diffusion by exploiting changing impedance across the front surface. Rigid diffusers, which exploit surface roughness, have to be deeper to operate over the same bandwidth, but create better diffusion. The mechanisms can be combined to form curved diffsorbers with good diffusion from a limited depth. Which is the correct diffuser to use depends on the application, with both acoustic and non-acoustic factors affecting the choice.

Figure 8 Sony Music M1, New York.

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