A BRIEF HISTORY OF ROOM ACOUSTIC DIFFUSERS

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"What wall shape has the highest possible sound diffusion, in the sense that an incident wave from any direction is scattered evenly in all directions?"

About three decades ago, Schroeder posed this question in his seminal paper outlining a new type of diffuser based on maximum length sequences[1]. Together, with his later ingenious designs based on quadratic residue[2] and primitive root sequences[3], he provided some possible answers to his question and revolutionized thinking about surface scattering in rooms. This has inspired others to research and develop new diffuser designs, drawing inspiration from disciplines as diverse as x-ray crystallography, optics and mobile telephony.

Concert halls

One application for these types of diffusers is within concert halls. The acoustics of a concert hall plays an important part in the music performance, as one of the roles of the hall is to embellish and enrich the sound. Outdoor music and concerts may be popular, but the sound quality is usually poor, because listeners only receive sound straight from the orchestra. There are no reflections from walls and the sound appears distant. Tourist guides to ancient amphitheaters often demonstrate a theater's remarkable acoustic properties by showing how a pin dropped on the stage can be heard by anyone in the audience. However, put an orchestra on such a stage and one would soon realize the weakness of the acoustics for classical music. In a well-designed, enclosed concert hall, reflections from the walls, ceiling and floor add reverberance and other characteristics to the sound—the sound comes alive. It envelops and involves the listener in the music making process.

Much of theater acoustic design concerns manipulating reflections by treating the surfaces from which the sound is reflected. A little over a hundred years ago Wallace Sabine demonstrated how surface absorption could be used to change the reverberation of a hall. Another wall treatment that controls the dispersion of the sound is surface diffusers. Currently, there is much debate about what role diffusers should play in a concert hall. One eminent concert hall designer regularly claims that too much diffusion is detrimental to the sound quality of the upper strings, while others have blamed the disappointing acoustics of some major concert halls on a lack of surface diffusion.

Treatments

To alter the acoustics of an existing room, some form of treatment is usually applied to the room surfaces. In concert halls, the sound can be altered by placing treatment on the walls and the ceiling (the floor already has seating and an audience). There are three basic forms of treatment—large flat surfaces, absorbers, and diffusers. Absorbers, such as carpets are not often used in large concert halls, because they remove sound energy from the space. Every bit of energy must be conserved because the maximum sound power output from an unamplified orchestra is limited.

The designer of a large concert hall usually chooses between large flat surfaces or diffusers. Figure 1 contrasts the spatial and temporal responses of these two surfaces. The

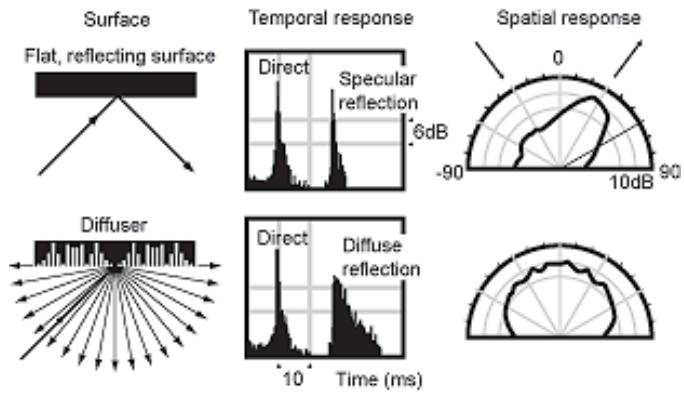

Fig 1. The spatial and temporal response of sound reflected from a plane flat surface and a diffuser. (After Cox and D'Antonio[15])

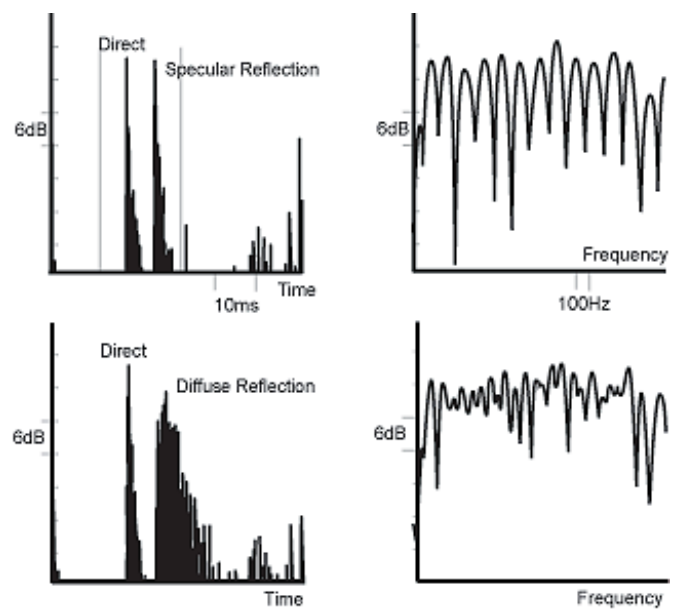

Fig 2. The time and frequency from a flat (top) and diffusing (bottom) surface. (After D'Antonio and Cox[16])

responses shown assume that there are no other surfaces present. A flat surface behaves in the same way that a mirror reflects light; the sound energy is preserved and concentrated in the specular reflection direction, where the angle of incidence and reflection are equal. The time response shows the similarity between the direct sound and the reflection. A flat surface does little to the sound except to change the direction in which the sound propagates. Figure 2 shows the resulting uneven frequency response (called comb filtering) leading to "coloration" of the sound. The timbre of notes is altered due to the emphasis and de-emphasis of the different frequency components.

Alternately, diffusers disperse the reflection both temporally and spatially. The time responses in Figs. 1 and 2 show reflections arriving over a longer time period. The frequency response shows less evidence of comb filtering than the flat surface and the peaks and troughs are uneven and randomly spaced. The sound is now a more faithful rendition of the original sound produced by the instrument and less coloration will be heard. Any non-flat corrugated surface will have some diffusing ability, but Fig. 1 shows a cross section through one of the specialized surfaces designed by Schroeder—in this case a quadratic residue diffuser.

Diffusers are used in a variety of ways, but most often they are used to avoid a particular acoustic defect. Their ability to spatially disperse sound is illustrated in Fig. 1, and might be exploited to overcome problems of uneven sound distribution over sections of the audience. A diffuser's ability to disperse sound temporally can be used to reduce echoes from the rear walls of auditoria. Sound often takes a long time to travel from the stage to the rear wall of a concert hall. If a strong reflection comes back from the rear wall to the front of the hall, this can be heard as an echo, especially if the rear wall is concave and focuses the sound. In older halls, the echo problem would have been mitigated by placing absorbent material on the rear wall to remove the offending reflection. However, the absorption removes acoustic energy and is undesirable. A modern solution is to use diffusers to disperse the troublesome reflections because this can be achieved without loss of acoustic energy. An example of using Schroeder diffusers on the rear wall of Carnegie Hall can be seen in Fig. 3.

Fig 3. Schroeder diffusers (QRDs®) applied to the rear wall of Carnegie Hall to prevent echoes. (After D'Antonio and Cox[17])

Fig 4. One period of two different Schroeder diffusers. Left—original design, right—fractal design. The diffusers are 0.6m wide, 0.6m high and about 0.2m deep.

Architectural trends

Wallace Sabine was the first person to apply "the scientific method" to room acoustic designs a little over a century ago. However, there are halls built before Sabine's work that are held to be great halls. An example would be the archetypal "best" concert hall, the Grosser Musikvereinssaal in Vienna. With these older halls, ornamentation and relief work appeared in a hall because it was the architectural style of the day. Walls were naturally diffusing.

In the twentieth century architectural trends changed and large flat areas appeared in many concert halls. The style of the day was to produce clean lines following a modernist style, and these surfaces then had little or no diffusing capability. While it is possible to design successful halls with flat surfaces (Symphony Hall Birmingham, UK), expanses of flat surfaces can lead to distortion due to comb filtering, echoes and other mechanisms.

Against this architectural backdrop, Schroeder developed his diffusers in the 1970s. An early motivation was the need to generate binaural dissimilarity at the listener, by promoting laterally propagating sound in concert halls. In the 1960s and 70s, various studies showed how binaural dissimilarity leads to a sense of envelopment, a greater sense of being involved in the music, and therefore, a "better" sound. The evidence for the beneficial effects of lateral reflections come from laboratory and field measurements on human perception, and these followed techniques pioneered in experimental psychology.

An example of Schroeder's original design can be seen in Fig. 4 (left). These surfaces offered acoustical consultants the designs for which they were looking—defined acoustic performance based on very simple design equations. While it is known that old-fashioned ornamentation produces diffusion, it does this in an ill-defined and haphazard fashion and most architects were no longer interested in such out-of-date styling.

One of the pioneering applications of Schroeder diffusers was by Marshall and Hyde in the Michael Fowler Centre, New Zealand[4,5]. Figure 5 illustrates the application. Large overhead surfaces were used to provide early reflections to the audience in the balconies. This was a design where a hall could have good clarity, and yet maintain a large volume for reverberation. Much of the volume is in the space behind the surfaces. Not many years before the design of the

Fig 5. Schroeder diffusers in the Michael Fowler Centre, New Zealand. (Photo courtesy of Dr. Harold Marshall of Marshall Day Acoustics)

hall, it had been established that lateral reflections were important[6]. The need for lateral reflections influenced Marshall and Hyde to apply diffusers to the large overhead surfaces rather than use flat reflectors.

Studios

It is a peculiarity of room acoustics research that most attention is paid to auditoria for classical music because the number of auditoria built each year is rather small. While diffusers found a place in the palette of treatments used in concert halls, it was actually in much smaller spaces, such as studio monitoring rooms, that many more diffusers were used. Around the time that Schroeder developed his diffusers, a new concept for listening and monitoring rooms was explored. This was the live-end-dead-end (LEDE) design[7], later refined into the reflection-free zone (RFZ) design. In these designs, diffusers are used to disperse early reflections that would otherwise arrive with little delay and at a high level. Without treatment, these early reflections (sometimes referred to as acoustic glare) would again color the timbre of the sound

Diffuser design

It became apparent to one of the authors (PDA) that the diffusers suggested by Schroeder were in-effect 2-dimensional "sonic crystals," that scatter sound in the same way that 3-dimensional crystal lattices scatter electromagnetic waves. Since the diffraction theory employed in x-ray crystallographic studies was applicable to acoustic reflection phase gratings, it was straightforward to model and design the Schroeder diffusers using techniques first developed in crystallography.

Figure 6 (left) illustrates the scattering from a Schroeder diffuser in polar coordinates. A source normal to the surface illuminates the surface. The polar response shows the one-third octave energy bands scattered from the surface as a receiver moves around the surface on a hemisphere. A series of lobes are seen, three in this case; these are grating lobes generated by the periodicity of the surface structure. Imagine viewing this polar response end on so that a set of three bright spots are seen; these are the type of images that x-ray crystallographers use to determine crystal structures. The acoustic problem being posed is somewhat different to x-ray crystallography. In crystallography, the diffraction patterns of the x-rays are used to determine an unknown structure. In the acoustic case, the inverse problem is solved—finding a surface structure that produces a desired polar response.

Sequences

In many ways, room acoustic diffusers act like optical diffraction gratings. Consider a mid-frequency plane wave incident onto a diffuser such as the one shown in Fig. 4 (left). Plane wave propagation occurs within the wells. If the surface is rigid, then plane waves are reflected from the bottom of the wells and re-radiate into the space with no loss of energy. The scattered pressure at some point external to the diffuser is interference among the radiating waves from the wells. All these waves have the same magnitude but different phases. The phase changes results from the time it takes the sound wave to go down and up each well. The Schroeder diffuser is a diffraction grating where the designer has control over the wave phases.

Schroeder's first step was to devise a surface that readily enabled the surface properties to be easily changed. His second step was to work out a method to determine an appropriate well depth sequence that generated a phase distribution on the surface of the diffuser and gave the desired reflected wave fronts. In inventing such a method, Schroeder turned to his favourite subject, number theory.

In the late 18th century, Carl Friedrich Gauss developed the law of quadratic reciprocity. Although best known to modern physicists for "Gauss's Law" that explains properties of electric fields, it is Gauss's number theory that led to the quadratic residue sequence that is used in the design of the quadratic residue diffuser. The formulation of a quadratic

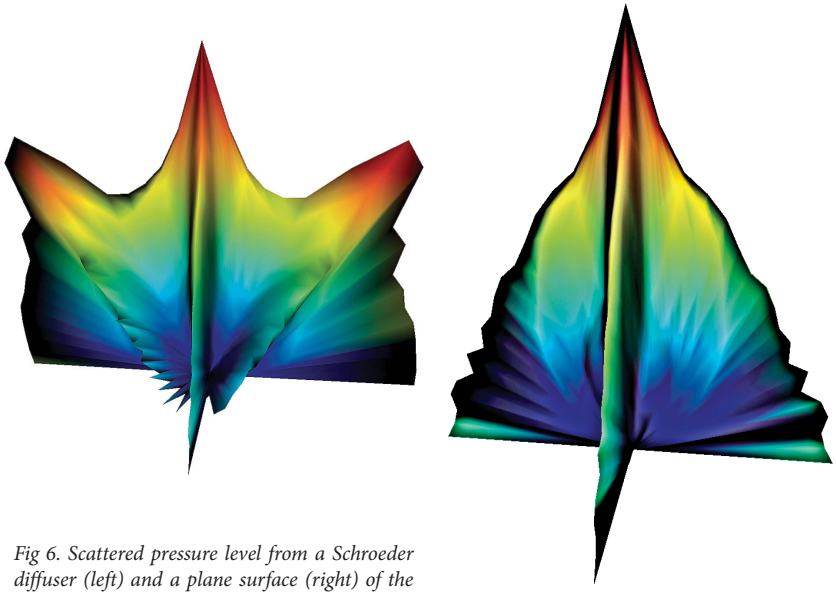

Fig 6. Scattered pressure level from a Schroeder diffuser (left) and a plane surface (right) of the same size.

residue sequence is based on a prime number. For the diffuser in Fig. 4 (left) the prime number is 7. The depth of the nth well is proportional to n^2 modulo 7, where modulo indicates the least non-negative remainder. So the third well has a depth proportional to 3^2 modulo 7 = 2. The sequence mapped out in this case is 0,1,4,2,2,4,1 that can be seen in Fig. 4. (The diffuser in Fig. 4 has zero depth wells on both ends, but these are constructed to be half the width). If this quadratic residue sequence is used to construct the diffuser, then the diffraction or grating lobes generated all have the same energy, as shown in Fig. 6 (left).

"Building on Schroeder's initial design, several revisions have been suggested to improve the performance."

To understand why number theory is useful, we need to turn to optical theories developed in the early 19th century by great physicists such as Fraunhofer. It is interesting to note that it is the Fraunhofer diffraction theory that has essentially been used by many researchers to examine the performance of Schroeder diffusers. This theory was aptly named after the first person to construct a diffraction grating in 1821—Joseph von Fraunhofer. The far field "scattering" from a reflection phase grating can be directly related by a Fourier transform to the distribution of the pressure reflection coefficients on the front surface of the diffuser. If our desire is to generate "even" scattering, then we need a distribution of reflection coefficients that are maximally random, or to be more precise, we need a set of reflection coefficients whose autocorrelation function is a delta-function. This is what pseudo-random number sequences provide—sequences of real or complex numbers with optimal autocorrelation properties. While it is possible to roll dice to generate well depths, number theory will provide sequences with better autocorrelation properties and consequently better scattering.

There are many other number sequences apart from those based on quadratic residues that can be used. Primitive root, Chu, and Luke sequences are three examples of sequences that have been examined as acoustic diffusers. Many of these sequences were originally developed for applications as diverse as astronomy, error-checking systems for computer and digital audio data, and mobile telephony. Rather incredibly, these sequences find a use in manipulating room acoustics. With roots back in 18th century mathematics, it seems almost impossible that these sequences, with their strange generation algorithms and modular arithmetic, should still be of use in room acoustic engineering. As Schroeder is fond of saying, number theory is, in many ways, unreasonably useful.

Enhancements

The basic Schroeder diffuser based on number theory sequences is an ingenious invention, however, aspects of its performance are not optimal. Building on Schroeder's initial design, several revisions have been suggested to improve its performance.

In room acoustics, designs must work over a wide bandwidth. A diffuser's wells need to be narrow and deep, and this makes the device very impractical. First, the structure becomes highly expensive to make, and second, the diffusers become very absorbing. If one uses very narrow and deep wells, it is possible to make a rather effective "absorber." Another issue is that if the well spacing becomes too small compared to a wavelength, then the diffuser behaves as though it is a surface with an average admittance rather than one with a complex spatial distribution of admittances. Inspired by chaos theory and fractals, a solution to this problem has been developed.

Element roughness

To cover many octaves, the diffuser needs to have "element roughness" on different scales. Using elements of different sizes is common in 2-way loudspeaker designs. For room acoustic diffusers, some elements need to have dimensions that are meters in size, and some need to have dimensions that are centimeters in size.

Fractals

Fractals are objects that have scaleable properties. The effect can be achieved for diffusers, as shown in Fig. 4 (right). In the surface shown, smaller diffusers are mounted within larger diffusers. The small diffusers scatter the high frequencies, and the larger diffusers scatter the low frequencies. This type of diffuser is rather fittingly named diffractal[8]. An example of applying a diffractal on the rear wall of a mastering room is shown in Fig. 7.

Phase gratings

Phase gratings, whether optical or acoustical, are normally periodic. For Schroeder diffusers, many periods of the device are stacked next to each other. Diffraction lobes that are designed to have the same energy are a function of periodicity, and therefore Schroeder's definition of optimum diffusion requires the structure to be periodic. These diffraction lobes represent energy concentrated into particular directions with a lack of reflected energy between. When there are many lobes this is not a problem, but this is not usually the

Fig 7. Gateway Mastering, Portland, ME showing a fractal diffusing rear wall (Diffractal®). (Photo courtesy of Gateway Mastering & DVD).

Fig 8. Scattered pressure level from a modulated, optimized, reflection phase grating.

case across the most critical octave bands. A better diffuser would be one that distributed the energy more evenly in all directions without lobes. Consequently there is an issue. Using the original number theory design, periodicity is required, yet this results in non-optimal performance. Angus[9], who showed that techniques developed for mobile telephony could be adopted for diffusers, devised a solution for this problem. These techniques are also applied to the design of loudspeaker and microphone arrays.

Spread spectrum techniques

Code division multiple access (CDMA) systems, using spread spectrum techniques, are used in mobile telephony to enable multiple users to use the same transmission bandwidth. Spread spectrum techniques take frequency (spectral) components and spread them over a frequency bandwidth. If the lobes generated by the Schroeder diffuser are viewed as spatial frequency components, the lobes will be spread spatially when spread spectrum techniques are used,. This is shown in Fig. 8, where the spread spectrum process has enabled the scattered energy to be redistributed from the three lobes shown in Fig. 6 to all directions (all spatial frequencies).

The most efficient way to achieve this spectrum spreading is to use a diffuser that is very asymmetrical, as shown in Fig. 9. The order of the diffusers is determined by chance with the diffuser placed in one orientation or opposite orientation. The diffuser array is no longer periodic and the periodicity lobes are suppressed. This produces a much more even polar response. While it is possible to use chance to determine the modulation sequence, it is better to use a properly-defined binary sequence. For a small number of diffusers, it is possible to task a computer to laboriously search for the best sequences, but this is rather slow and inelegant. It is often much better to use those "unreasonably-useful" sequences that mathematicians have been producing for many centuries. The first sequence used for modulating diffusers was the maximum length sequence, also known as a Galois field. Maximum length sequences are based on mathematics developed by a 19th century mathematician Evariste Galois. Galois's maximum length sequences are used widely in digital systems. In acoustics they are probably best know for being an efficient signal for measuring linear time-invariant systems.

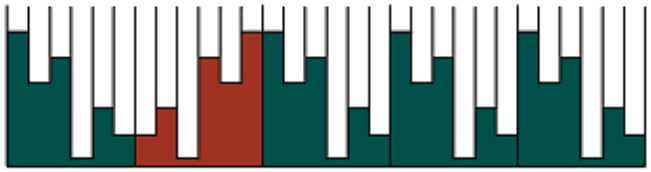

Fig 9. A cross-section through a modulated diffuser array based on an N=7 primitive root diffuser.

Reflection phase grating diffuser

The reflection phase grating diffusers have become vernacular in modern recording and broadcast studios. However, their appearance may be an impediment to their use in general architectural spaces, especially given current tastes in architecture and interior design. The diffuser's appearance is not in keeping with modern architectural designs that now tend to use curves and more organic shapes. With Schroeder diffusers, the acoustic treatment is imposing a distinctive visual aesthetic. While there are architects who like form to follow function, most architects want to determine the visual aesthetic themselves. If an architect thinks a diffuser looks ugly, it is unlikely to be used even if the treatment is vital to the acoustic design. Consequently, there is a need for designs that complement modern architectural trends.

Figure 10 shows a modern diffuser design on a concave wall. This is a curved diffuser designed to visually complement the shape of the room, while providing the required acoustic performance. The diffuser disperses reflections from the concave wall that would otherwise lead to sound being focused in a particular spot. Figure 11 shows the polar response for the wall alone. It shows that the scattered energy level is much greater for the receiver at the focal point. In treating this focusing problem, it would have

Fig. 10. Optimized curved surface in the Edwina Palmer Hall, UK. (Photo courtesy of Arup Acoustics)

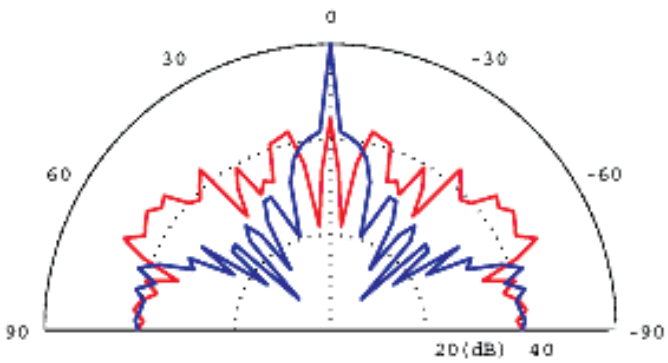

Fig. 11. Scattering from a concave arc compared to an optimized curved diffuser. Blue: concave arc, Red: optimized curved diffuser. (After Cox and D'Antonio[15]).

been possible to add absorption on the wall to remove the reflections, but this would have removed energy from one side of the orchestra, and these reflections are needed so the musicians can hear both themselves and others. Without these the musicians would find it harder to keep in time, form a good tone and blend with the orchestral sound. The solution to the focusing wall is to use diffusers to remove the focusing effect, while preserving the acoustic energy. The polar response after treatment is shown in Fig. 11. It illustrates the effectiveness of the diffuser in removing the "hot-spot."

Numerical optimization

To design this type of diffuser requires a new methodology[10], and for this it is possible to use numerical optimization, a method commonly used in engineering. Numerical optimization may not have the efficiency and elegance of number theory design, but it is extremely effective and the designs it produced are robust. Numerical optimization tasks a computer to search to find an optimum solution to a problem. For acoustic diffusers, the computer looks for the surface shape that gives optimal scattering. The procedure follows an iterative scheme. The computer starts by guessing some curved surface shape. The scattering from the surface is predicted in terms of the polar response. The predicted polar response is then rated for its quality in terms of a figure of merit. The computer can then use a process of trial and error, changing the surface shape to try and optimize the figure of merit. The process continues until an optimum design is found. The search process cannot be completely random because this would take too much time. Fortunately, mathematicians have developed many algorithms to allow the search to be done efficiently. Currently, the most popular algorithm is to model the problem as an evolutionary process, using survival of the fittest principles to carry out an efficient search. The technique is called a genetic algorithm.

The genetic algorithm

A genetic algorithm mimics the process of evolution that occurs in nature. A population of individuals is randomly formed with their genes determining the traits of each individual. When designing diffusers, the genes are simply a set of numbers that describe the curved surface shape. Each individual (or shape) has a fitness value (figure of merit) that indicates how good it is at diffusing sound. Over time, new populations are produced by combining (breeding) previous shapes, and the old population dies off. Pairs of breeding parents produce offspring with genes that are a composite of their parent's genes. The offspring shape will then have features drawn from the parent shapes, in the same way that facial features of a child can often be seen in their parents. A common method for mixing the genes is called multi-point cross over. For each gene, there is a 50% chance of the child's gene coming from parent A, and a 50% chance of the gene coming from parent B.

If all that happened was a combination of the parent genes, then the system would never look outside the parent population for better solutions. A fish would never get lungs and walk about on the land. As with biological populations, mutation is needed to enable dramatic changes in the population of shapes. This is accomplished by a random procedure whereby there is a small probability of any gene in the child sequence being randomly changed, rather than directly coming from the parents.

Selecting shapes to "die off" can be done randomly, with the least fit (the poorest diffusers) being most likely to be selected. In biological evolution, the fittest are most likely to breed and pass on their genes, and the least fit the most likely to die. This is also true in the artificial genetic algorithms used in numerical optimizations. By these principles, the fitness of successive populations should improve. This process is continued until the population becomes sufficiently fit so that the best shape produced can be classified as optimum.

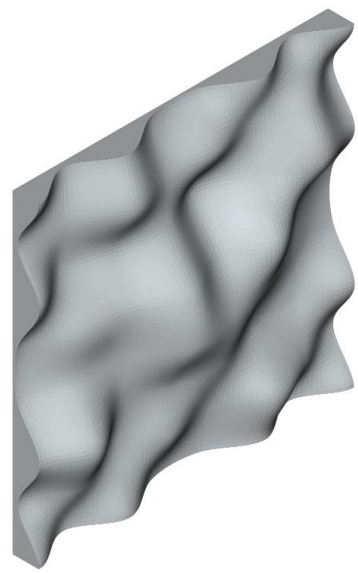

Figure 12 (top) shows an example of another optimized curved surface. Because it is now known that periodicity reduces dispersion, this surface has

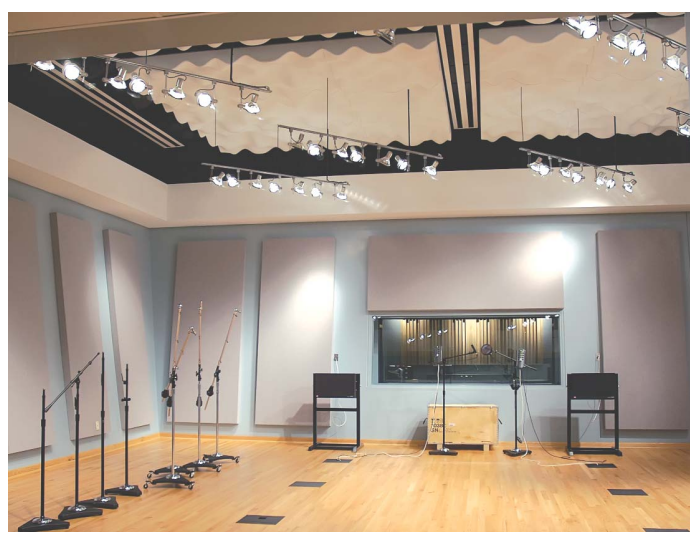

Fig 12. (top) An optimized curved surface designed to be tiled in a modulated array. (bottom) Ceiling Waveform treatment at KTSU, Houston, TX. (Photo Courtesy of HFP Acoustical Consultants)

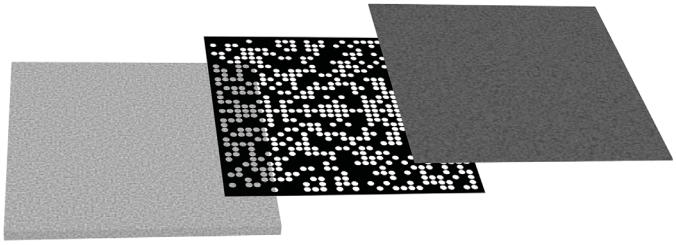

Fig. 13. Construction of a hybrid surface_left, porous absorber; middle, the mask; and right, cloth. (After Cox and D'Antonio[15])

been optimized to be both asymmetrical, and yet to have identical symmetrical edges so that the surface can be rotated and tiled in any direction. Consequently, architects can now manipulate the appearance and trade this off against acoustic performance. They can chose a periodic design, and accept the performance cost of the grating lobes, or they can use a more random appearance knowing that the acoustic performance will be enhanced. An example of this 2-dimensional bicubic waveform is shown in a ceiling application in Fig. 12 (bottom).

Hybrid diffusers

While it might appear that optimization is the answer to all possible diffuser designs, there is still interest in using number theories since the optimization problem becomes prohibitively large to solve when the diffuser has a large number of wells. However, number theory has suggested a different kind of diffuser—a hybrid surface. The construction of a hybrid surface is shown in Fig. 13. It consists of a piece of porous absorbent material that is covered with a perforated mask. The mask may be hidden from view by a thin piece of acoustically transparent cloth or exposed in wood or metal. This is essentially a Helmholtz absorber, but with an uneven distribution of the holes. At some mid-frequency, high absorption results that decreases as the frequency increases. At these upper frequencies where only partial absorption occurs, the uneven distribution of the holes causes reflected energy to be diffused. To get good dispersion, a pseudo-random binary sequence that has an autocorrelation function similar to a delta-function is used. When zero occurs in the sequence a hole is drilled in the mask. When one occurs in the sequence, the mask is left untouched. Any repetition in the sequence will lead to lobes, so sequences are needed that are dissimilar from shifted versions of itself. Again, number theory can provide many different sequences.

Angus[11] first examined the performance of these devices using maximum length sequences. These are the same sequences that were used originally to modulate Schroeder diffusers and also used by Schroeder in his first paper on diffusers. A problem that occurs is that maximum length sequences are a one-dimensional string of ones and zeros. For hybrid surfaces, a two-dimensional array of numbers is required. Again, there are a number of techniques for forming two-dimensional binary arrays[12] that can be exploited. One of the commonly used techniques is referred to as the Chinese remainder theorem.

An example of a Chinese remainder problem was posed by Sun Tsu Suan-Ching in the 4th century AD[13].

"There are certain things whose number is unknown. … Divided by 3, the remainder is 2; by 5 the remainder is 3; and by 7 the remainder is 2. What will be the number?"

(One answer to the above problem is given at the end of the article.)

From this rather strange start, a method for sequence folding can be generated that has been used in coding systems, cryptology, and x-ray astronomy. The mask shown in Fig. 13 is a maximum length sequence of length 1023 that has been folded into a 31x33 array using this process.

The problem with maximum length sequences is that they are devised for systems that are bipolar, consisting of plus ones and minus ones. The hybrid surfaces produce no reflections (reflection coefficient ≈ 0) and reflections (reflection coefficient ≈ 1) and so are inherently unipolar. This can be a problem when designing diffusers. Most electronic systems have bipolar capabilities that produce signals of the opposite sign. This is often exploited to reduce the out-of-phase autocorrelation function. Fiber optic systems, on the other hand, are intrinsically unipolar because the light is either on or off. These optical sequences can also be exploited in hybrid diffusers; however, the number of sequences with the right balance of 0s and 1s are rather small.

A problem with planar hybrid surfaces is that energy can only be removed from the specular reflection by absorption. If it were possible to exploit interference by reflecting waves out of phase with the specular energy, then it would be possible to diminish the specular energy even further. One solution is to bend or corrugate the surface, breaking up the specular reflection component. This type of design is proving to be very popular in studio control and listening rooms. More recently it has been shown that the specular reflection can also be dispersed by using a diffuser based on a ternary sequence that nominally has surface reflection coefficients of zero, minus 1, and plus one[14]. These reflection coefficients are made using wells, absorbent patches and rigid sections respectively.

Figure 14 shows the scattering from two hybrid absorber-diffusers compared to a plane surface. The hybrid surfaces provide dispersion, with the performance of the ternary sequence being best because of its ability to generate more obliquely propagating sound, reducing the specular energy by exploiting wave superposition as well as absorption.

Summary

Much has been learned about the design of room

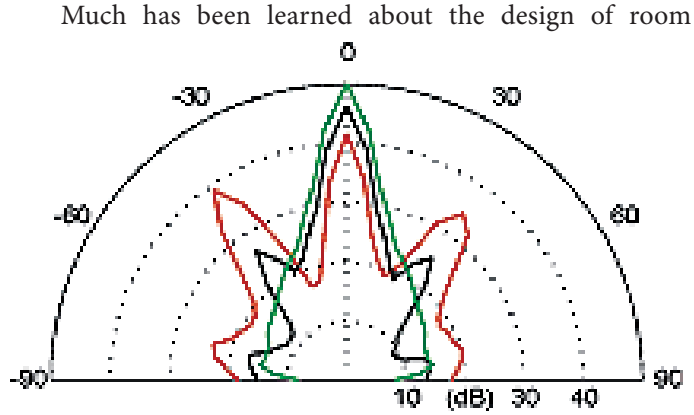

Fig. 14. Scattering from three diffusers: Black: binary diffuser; Orange: ternary diffuser showing significantly more lateral scattering, and Green: plane surface[18].

acoustic diffusers over the last three decades. Alongside the designs outlined above, a sizeable literature has developed explaining how to measure, predict, and characterize the effects of surface diffusers. In the same way that absorption coefficients are specified, proof of performance standards have now been established that allow designers to specify coefficients relating to the amount of sound scattered and the quality or uniformity of the diffusion. Yet many questions still remain unanswered. Perhaps the most important question to answer is how much diffusion should be applied, and where diffusers should be used. While acoustic designers have produced many innovative new designs, the understanding of where to apply diffusers lags behind and is still largely based on precedence. Maybe this is why eminent acousticians can still disagree on the role of diffusers within auditoria; or maybe it is just a case of individual taste.

Ultimately, whether a diffuser is used or not is a decision usually made by an architect who often has little or no acoustic training. The key to good diffuser design is to find forms that complement the architectural trends of the day. The diffuser must not only meet the acoustic specification, it must fit in with the visual scheme required by the architect. This means that diffuser design has moved away from its roots in number-theoretic reflection phase gratings. However, much of what has been learned from decades of work on Schroeder diffusers is still being applied today. **AT**

One answer to the Chinese remainder problem was 23.

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