

Generating Acoustic Diffuser Arrays with Shape Grammars

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ABSTRACT

This paper presents research on a rule-based approach to designing creative acoustic diffuser arrays. A shape grammar-influenced design method is specified that uses shape rules to recursively design arrays of quadratic residue diffusers (QRD) in ways that are neither mechanical nor deterministic.

Author Keywords

Architectural acoustics; diffusion; Schroeder diffuser arrays; shape grammars; design computation

1 INTRODUCTION

The shapes of surfaces have a significant impact on the acoustic quality of spaces, yet design processes for architectural acoustics are often highly conventional. With the exception of notable examples [8], acoustical designers have preferred to use knowledge from historical examples, elementary acoustic shape concepts from known equations, and templates from standard principles of performative success. This is particularly true for surface treatments using diffuser products. Acoustic diffusers [4] are surfaces that are not flat and exhibit geometries on the surface that cause reflections to disperse not only in reflected directions, but also in phase and temporal distribution. These non-flat geometries have taken various common forms such as hemispheres, pyramids, arcs, fractals, and number theory generated shapes such as Schroeder diffusers. Surface treatments for diffusion typically use prefabricated products aggregated in ways that perform sufficiently but are visually predictable and monolithic. *This paper addresses the critical issue of design homogeneity in architectural acoustics by proposing a shape grammar approach to designing acoustic diffuser arrays.* This paper will first review principles of diffusion and diffusers and give an overview of previous work with applied shape grammars, propose and demonstrate the diffuser grammar, and discuss how this visual computing method suggests further possibilities of creative and

intentional designs of diffuser arrays that consider performative and aesthetic criteria.

2 ACOUSTIC DIFFUSION AND DIFFUSERS

Acoustic diffusers are geometric surfaces that are designed to break up sound waves and create reflections in different directions [4]. Practically, diffusers are deployed in rooms to mitigate acoustic artifacts such as strong specular reflections or flutter echoes [10]. To alter these reflections, rough surfaces are needed to reflect the initial sound wave back at different angles and phases. Diffuser designers have used geometry, number theory, and performance optimization to design diffusers for desired time and spatial responses [4]. In this section, a background of diffusers and quadratic residue diffuser (QRD) design will be presented.

2.1 Background to Diffusion

When a plane wave strikes a perfectly reflective flat/smooth surface, the resultant wave reflects at the same amplitude as the initial wave and reflects back at an angle equivalent to the incident wave [12]. Diffusion is a frequency dependent phenomenon; thus, the size and depth of the surface geometries affect the effective frequencies of the diffusion. Deeper geometries allow for lower frequency diffusion and shallow geometries diffuse higher frequencies. The depth of the geometry is therefore related to the wavelength of the design frequency of the diffuser. A specific example of this relationship is given below for the quadratic residue diffuser depth. With purposeful acoustic design, these reflections can reinforce the desired sounds and increase factors such as speech intelligibility [10]. Specular reflections can also cause acoustic defects such as flutter echo or acoustic focusing [10]. Waves that strike rough surfaces are diffused: the initial wave is reflected into several new waves that propagate at lower amplitude, at various angles, and at different phases. Previous studies have demonstrated the time and directivity difference of pure reflection, absorption, and diffusion (Figure 1). Careful use of diffusers can suppress flutter echoes and acoustic fluttering, can promote spaciousness in a room, and can help control early reflections in large spaces

[10]. Due to the temporal distribution of the reflected wave, the frequency response of the reflected wave is also be altered by the diffuser [4]. Users suggest that the effect of too much diffusion can create spaces where source localization is difficult and desired sounds are not being reinforced; however, more rigorous studies are required in this area [3]. For example, Cox and D'Antonio suggest that the apparent size of the reflected image is broadened with a diffuser [4]. Optimizing the placement, amount, type, and spatial/temporal properties of diffusers is critical to the acoustical success of a space.

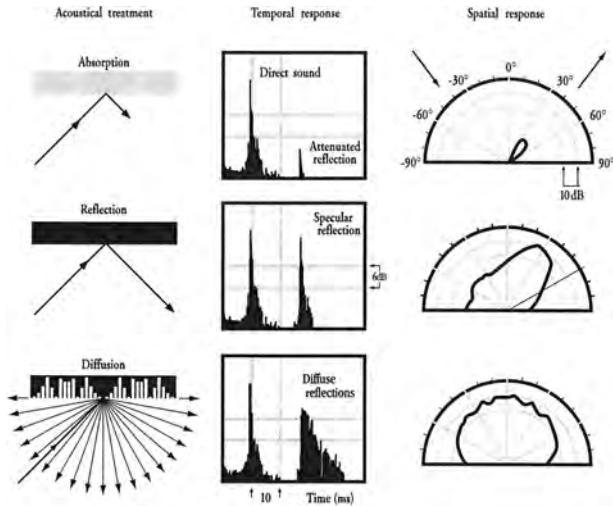


Figure 1. Characteristics in temporal and polar response of absorption, reflection and diffusion of an incident sound wave. [4]

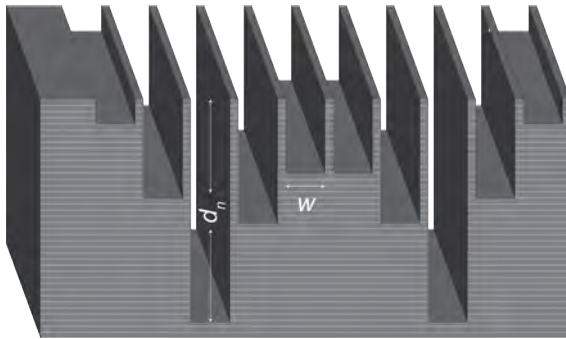


Figure 2. Example of an N11 QRD, showing relationships between the well width, well depth and wall thickness.

2.2 Quadratic Residue Diffusers

Manfred Schroeder invented the phase grating diffuser [14], consisting of a series of wells of different depths separated by thin fins. When a wave strikes a Schroeder diffuser, the waves reflect from the bottom of each well. Due to the differences of depth, the reflected waves have a different phase associated with the depth of each respective well. This phase difference causes a diffuse spatial distribution of reflected sounds. Thus, the well design is the primary parameter that dictates spatial and temporal properties of acoustic diffusion. The simplest diffusers are one-dimensional, corresponding to wave diffusion in only one

plane, perpendicular to the fins of the diffuser [4]. Two-dimensional diffusers can be designed with perpendicular and parallel fins to diffuse sound waves into both planes. Due to the physical dimensions of the wells, diffusers are frequency-dependent [4]. Figure 2 shows a schematic diagram of a Schroeder diffuser. The well depth is derived:

$$w = \frac{\lambda_{min}}{2}$$

where

$$\lambda_{min} = \frac{c}{f_{max}}$$

In this equation, w is the well width, λ_{min} is the minimum wavelength before cross modes emerge, c is the speed of sound, and f_{max} is the maximum frequency of diffusion. Practically, well widths are at least 2.5 cm and are commonly 5 cm [4]. Narrow well widths can cause unintended absorption from the viscous boundary layer, and wide well widths limit the frequency range of effective diffusion. The depth of the n^{th} well is governed by the following equation:

$$d_n = \frac{s_n \lambda_0}{2N}$$

where s_n is the sequence number, λ_0 is the design wavelength, and N is a prime number that corresponds to the number of total wells in the diffuser. For a design frequency, f_d , the desired wavelength can be calculated from:

$$\lambda_0 = \frac{c}{f_d}$$

It can be seen through these calculations that a high design frequency, f_d , results in shallower depths, and lower design frequencies will lead to deeper wells. This relationship of well depth to frequency is also shown in Figure 3. For Schroeder diffusers, a mathematical sequence is the basis for the well depth derivation. The sequence number, s_n , can be generated using maximum length sequences, primitive root sequences, Legendre sequences, amongst a variety of possibilities. The quadratic residue sequence (QRD) continues to be one of the popular choices, derived from the following equation:

$$s_n = n^2 \bmod N.$$

In the case where $N=11$, $s_n = \{0, 1, 4, 9, 5, 3, 3, 5, 9, 4, 1\}$.

Combining the process from above, it can be shown that for a design frequency of 1000 Hz and speed of sound of 343 m/s, the well depths, for an $N=11$ QRD diffuser is

$$d_n = \{0, 16, 62, 140, 78, 47, 47, 78, 140, 62, 16\} \text{ mm.}$$

2.3 Evolution of Diffusers

Within these phase grating designs, there have been several standard designs that are commonly used in the industry, with few variations since their invention. One such variation consisted of an "L-shaped" well to essentially make a 2-dimensional QRD diffuser [6], but this has not seen wide

implementation in the market. Other variations also include thin panel designs, sloped wells, and even an embedded QRD inside a well of a larger QRD. While there has been large scale deployment of diffusers in spaces like concert halls, the computational approach for simulation of these large-scale deployments has been more limited. There are studies that show detailed directivity and temporal responses to individual diffusers or small arrays of diffusers [4]; but for these larger room simulation models, simpler diffusion and scattering coefficients are utilized. Developing better computational approaches to quantify large surfaces of diffusion that can better inform computer simulation methods is an area of future study.

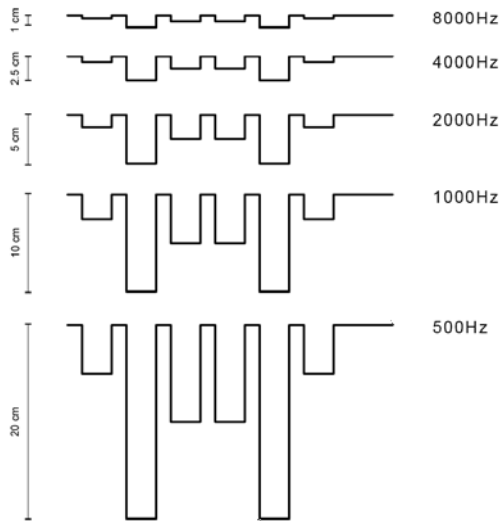


Figure 3. Schroeder diffuser sections for a N=7 design with different design frequencies, from 500Hz to 8000Hz.

3 SHAPE GRAMMARS

Shape grammars are a computational design methodology that use the notion of *recursion and embedding* for computing with shapes, as an extension of Turing’s “recursion and identity” for computing with symbols [11]. Shape grammars have been used to define *languages* of design in nearly all areas, but little has been done to combine them with acoustics. This section will review the origins of shape grammars, their basic formalism, and the range of previous applications in design fields.

3.1 Fundamental Principle: Embedding

Shape grammars are distinguished from other theories of computation through their use of *embedding*, which grounds them as primarily a *visual* enterprise. Symbols (like points), are 0-dimensional objects, which means they can only be identified as themselves. Shape descriptions of things can operate under the notion of identity, but also under the notion of embedding which privileges the infinite possibilities of what one can see. This can be illustrated by looking at a line:



Lines can be identified as themselves. However, one could also visually identify any number of other lines embedded in that line (shown in red):



This is true for any shape made of lines, faces or solids (1, 2, or 3-dimensional shapes). Shape grammar theory and its applications have demonstrated how shape-based generative systems are more expansive than symbol-based systems because they benefit from the notion of embedding. Working with shape descriptions lets designers work visually, yet rigorously through rule-based shape transformations. Shape grammars rely on a basic formalism, described below.

3.2 Basic Shape Grammar Formalism

The shape grammar formalism has evolved significantly since it was first introduced. Initially Stiny and Gips [18] relied heavily on linguistic analogies that formulated a rigorous mathematical apparatus [16]. Shape grammars have since been simplified to sets of shape rules, labels and weights, and schemas, which classify rules.

3.2.1. Shape Rules

A *shape rule* is written in the form $A \rightarrow B$, where A is a labeled shape that is transformed into a labeled shape B [16]. An example of a shape rule that aggregates \square might be:

$$\square \rightarrow \square \square$$

Each time the rule is applied, a new \square is copied and pasted:

$$\square \Rightarrow \square \square \Rightarrow \square \square \square \Rightarrow \dots \Rightarrow \square \square \square \square \square$$

Shapes can be transformed through spatial transformations (translation, rotation, reflection, scaling), Boolean operations (union, intersection, subtraction), and combinations of the two. When applied recursively, shape rules can generate new and surprising shapes in a rigorous yet and intuitive manner.

3.2.2. Labels and Weights

Shape rules can be augmented by *labels and weights*, which restrict rules or specify how they are applied. *Labels* are 0-dimensional symbols, treated as points rather than shapes:

$$\square \rightarrow \square^{\circ}$$

Weights can specify line type and thickness. Planes can have additional graphic properties, such as texture, color, or tone:

$$\square \rightarrow \square$$

$$\square \rightarrow \blacksquare$$

$$\square \rightarrow \blacksquare$$

Practically, *weights* can serve as a means of associating shape descriptions with physical properties of the designs they represent [17]. Such properties could include structural

or other performative criteria, material specifications, or methods of construction and fabrication.

3.2.3. Schemas

Parametric shape grammars, more commonly known as *schemas*, extend shape grammars by generalizing shape rules into schemata written in the form, $x \rightarrow y$, where x and y are variable terms that can be assigned any parametric shape. The shape rule $\square \rightarrow \square$ can be generalized: $x \rightarrow x+t(x)$, where x can include any parametric variation of \square according to well defined dimensioning and proportion rules. The “copy and move” transformation is generalized as an additive schema $x+t(x)$, where an identity schema $x \rightarrow x$ keeps the original shape in place and a translation of that shape $t(x)$, is added. Schemas are important for design because they serve as universal rules of formation that reveal how shape rules are related, and new ways to use them.

3.3 Review of Shape Grammar Applications

A significant portion of shape grammar scholarship has been dedicated to developing computational mechanisms that demonstrate expanded possibilities of architectural designs in particular styles. Shape rules and schemas have seen broad success in studying historical bodies of architecture such as the plans of villas by Renaissance architect Andrea Palladio [19], houses by Frank Lloyd Wright [7], and the houses of Alvaro Siza at Malagueira [5]. The shape grammar systems defined by these architectural studies shed light on the generative possibilities of their respective architectural languages. While successful in defining generative systems, their production does not extend beyond shape descriptions. A specialized sub-set of shape grammars were introduced that could handle physical and performative properties of the designs they described. In 1991, William Mitchell introduced *functional grammars* [13] for generating designs of shed structures. This important work inspired shape grammar formalisms in other fields such as electro-mechanical engineering [2] and product design [1]. In structural engineering, shape grammars have been used for designing truss structures [15]. More recently, a trans-typology structural grammar was developed that combined shape grammars and graphic statics [9].

Despite numerous applications of shape grammars across virtually all areas of design, very little has been done with acoustics. A recent paper [20] proposes a shape grammar that generates absorber panels, however, performance criteria are not rigorously integrated into how the panel shapes are generated to make an array. Furthermore, only one design is proposed, which seems counter-intuitive to using shape grammars in the first place. The grammar proposed here aims to directly integrate the form-performance relationship of Schroeder diffusers.

4 A LANGUAGE OF DIFFUSION

One advantage of using QRDs for diffuser surface treatments in architectural acoustics is they have a reliable form-performance relationship. Wall treatments with QRDs, typically consist of prefabricated panels that meet desired

performance criteria; aggregated with little or no variation over an entire wall surface (Figure 4). While these arrays may perform sufficiently and predictably, they are visually uninteresting and monolithic. *Why are the rules of aggregation for diffuser panels so unchanging?*

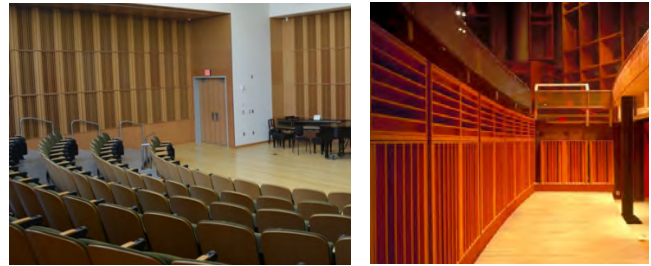


Figure 4. Examples of how Schroeder diffuser products are typically deployed in diffuser wall treatments [21, 22].

This paper addresses the critical issue of design homogeneity in architectural acoustics by proposing a shape grammar methodology for designing quadratic residue diffuser arrays. The diffuser grammar is a two-dimensional parametric shape grammar that uses labeled generative shape descriptions of quadratic residue diffusers as their basic element. QRDs are simple enough that a two-dimensional shape description is sufficient for computing these types of arrays. A coupled form-performance relation is described with labeling systems and weights to associate shape descriptions of QRDs with their physical and performative properties. Weights will indicate a design frequency and the number of wells of a panel. Labels will indicate the orientation of the panel, and direction of their well sequence. The 5-steps of computing (Figure 5) are specified in this section. Computing begins with an initial labeled shape; shape rules are applied recursively. Grid rules aggregate initial shapes into arrays, grid-configuration rules make compound transformations, and form/frequency rules associate shape descriptions with material and performative properties. Computing ends either when no more rules can be applied or when the designer chooses to stop because they like what they see.

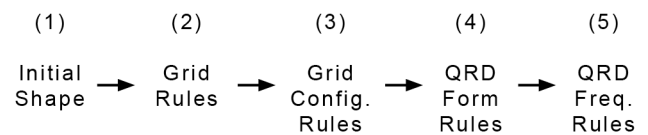


Figure 5. Computing Steps for QRD Shape Grammar

4.1 Initial Labeled Shape

Diffusion arrays in this grammar stem from a square panel. The grammar starts with an initial shape: a labeled square that represents a 60cm x 60cm diffuser panel. An *initial shape rule* (Figure 6) places a labeled square somewhere in the diffusion area. At this stage, the panel does not specify diffuser form or performance properties. The labels on the square serve to indicate the center of the panel with a dot, and to orient the panel in space with an arrow. The arrow-dot label indicates a one-dimensional QRD panel. Later, the initial labels will be replaced with weights and other label

systems to specify the number of wells, the direction of the well sequence, and the design frequency of the panel.

4.2 Grid Rules

Grid rules aggregate the initial shape and manipulate the labels in those initial shape configurations (Figure 7). Rules (G1) and (G2) are aggregation rules that copy and paste the initial shape according to the schema $x \rightarrow x+t(x)$. Together, they can generate rectangular arrays, but also irregular or asymmetrical configurations of squares. Rule (G4) changes the initial shape for a one-dimensional QRD, to an initial shape for a two-dimensional QRD panel. The rule removes the red circle, and adds and rotates a second arrow that connects to the first. Rule (G3) changes the orientation of an initial shape, which equates to rotating a one-dimensional QRD panel from a vertical to horizontal orientation, as shown in the image on the right of Figure 3. Rule (G5) rotates the initial shapes for two-dimensional diffuser panels. Both rotation rules operate according to the schema, $x \rightarrow t(x)$.

4.3 Grid-Configuration Rules

Grid rules are a powerful means of introducing variation and change to arrays of diffuser panels by graphically distinguishing between one and two-dimensional diffusers and introducing the ability to rotate their labeled shape descriptions in a design. These transformations can be tedious however, because they apply to one panel at a time. Grid-configuration rules are an emergent class of compound diffuser rules that use *embedding*. These rules let a designer invent new rules as they work. Groupings of labeled shapes can be picked out to apply multiple grid transformation rules simultaneously. The rules (Figure 8) change pairs of labeled squares from one to two-dimensional diffuser descriptions and also pick out square, T-shaped, L-shaped grid figures to perform compound rotations. Though simple, these rules illustrate how expansive the design possibilities can be when new compound rules such as these are written.

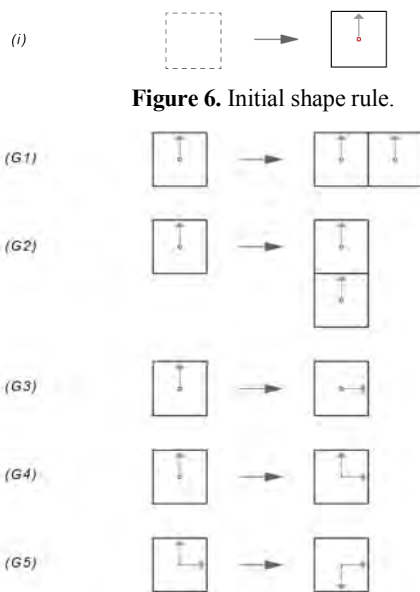


Figure 6. Initial shape rule.

Figure 7. Grid Rules

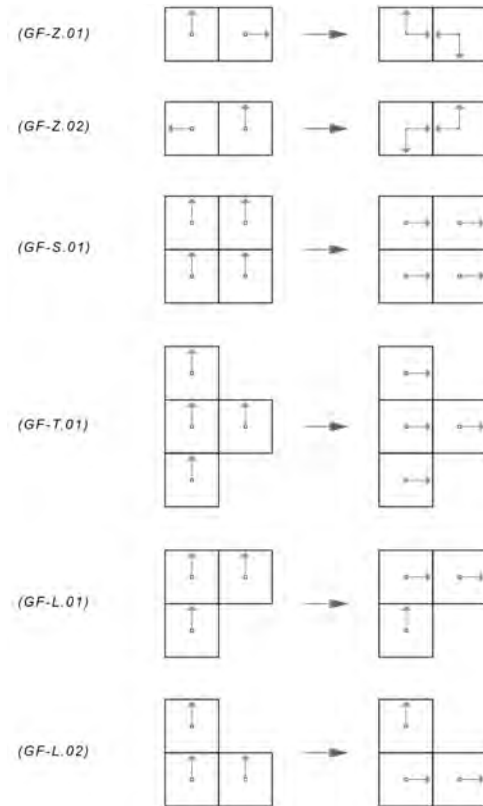


Figure 8. Grid-Configuration Rules.

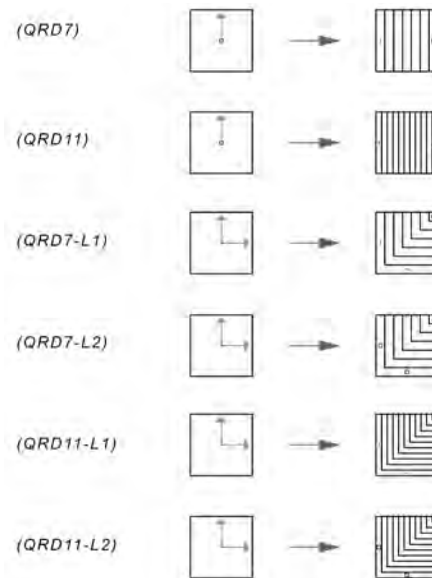


Figure 9. QRD assignment rules specify types of QRD panels.

4.4 QRD Form Assignment Rules

A *form-performance relation* of Schroeder diffusers in the grammar is specified with labeling and weight systems. QRD form and performance rules associate physical and performative properties of diffusers with their shape

descriptions. *QRD form assignment rules* (Figure 9) specify the number of wells the diffuser panel will have. A label system indicates the direction of the well-depth sequence, which includes a value of zero (see sample sequence in section 2.2). The circle indicates the location of the zero-depth well. Rules (*QRD7*) and (*QRD11*) removes the arrow-dot labels from initial shapes and draws the fins of one-dimensional QRD panels. A 60 x 60 cm panel could have as few as seven wells and as many as eleven. Two-dimensional diffuser panels with L-shaped fins [7] are specified in the grammar as well. QRD form assignment rules can be applied at any time during a computation, however they terminate grid manipulations. To change the orientation or type of QRD panel in a design, the grid-figure rules have to be applied in reverse to return the panel back to an initial shape with an arrow-based label.

4.5 QRD Frequency Assignment Rules

QRD frequency assignment rules specify the design performance of panels in a design. These rules apply a tone to the QRD shape descriptions. Common design frequencies for diffusion surface treatments were selected and assigned tones. The rules look for the well-depth sequence labels applied in the previous step and apply different tones across the array. Figure 10 specifies five design frequency rules that use the one-dimensional well-depth sequence labels. Figure 11 specifies frequency rules that include the use the other two well-depth sequence labels for two-dimensional diffusers, with the same range of frequency-indicating tones. Applying different tones in a single array presents opportunities to generate multi-band diffuser treatments. Once the two-step form-performance assignments have been made, a designer can make material and fabrication specifications for a design based on the visual descriptions generated by the grammar.

5 EXAMPLE COMPUTATIONS

Shape grammars have the ability to not only generate known designs, but also other surprising and unexpected designs in the language. Figure 12 shows simple step-by-step computations using rules (*G1*) and (*G2*) to make 2x2 panel arrays. Rule (*G3*) rotates panels to make patterns that are recognizable, and include the designs in [Figure 3]. More complex arrays can also be generated by applying rules differently – and to larger numbers of panels. Figure 13 shows examples of 4x4 panel arrays generated from grid-configuration rules and 1D QRD panels oriented either vertically or horizontally. Figure 14 shows two other example computations that use parametric variations of the L-shaped grid-configuration rules. Figure 15 gives examples of larger QRD arrays that produce visually evocative, surprising, and irregular patterns.

6 DISCUSSION AND FUTURE WORK

The grammar demonstrates how designing diffuser arrays can be open-ended and creative. By challenging the manner in which QRD panels are typically deployed, this paper addresses *how to design with acoustic diffusers* in architectural acoustics.

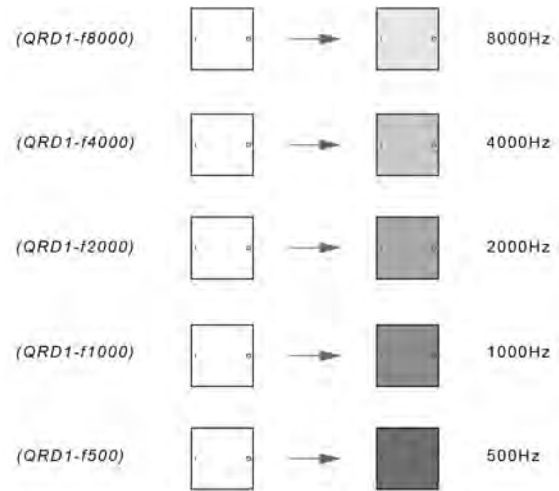


Figure 10. Sample 1D QRD assignment rules to specify frequency.

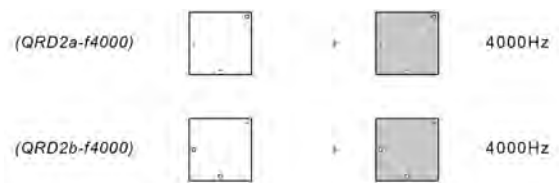


Figure 11. Sample 2D QRD assignment rules to specify frequency

Though already quite expansive, the grammar should be expanded further:

Initial shapes – the rules in this diffuser grammar currently is based on grids of a common 60cm x 60cm square QRD panel design. Although rules have only been written for one and two-dimensional diffusers with either seven or eleven wells, one could easily specify rules for QRD versions that have eight, nine, or ten wells on the same size panel. The physical dimensions of a physical QRD panel are ultimately dependent on the number of wells, the design frequency and also fabrication limitations, so other initial shapes could be specified for panels of other sizes/well counts.

Grid and grid-configuration rules – configuration rules have the most expansive potential to produce new and unexpected designs of diffuser arrays in this grammar because they capitalize on the notion of embedding. By continuing to find shapes embedded in the panel grids, new configurations of panel types, well-counts, or even frequency could be specified. For instance, one could imagine several more grid-figures rules that use parametric variations of L's, T's, rectangles. In addition to making compound rotations, grid-configuration figure rules could be extended to specify compound additions of panels, that would generate even more surprising possibilities of diffuser arrays. They could also begin erasing grid lines in order to describe new panels whose new shape comes from fusing visual descriptions of panels together in a computation. The labeling systems in the

grid rules are currently quite restrictive. They assure that any array produced by the grammar is made up of known QRD panels, which severely limit the possibility for the recombination of panels. Future work on diffuser grammars should strive to loosen the labeling rules and permit for unexpected scaling and overlapping to occur. Future developments should also be focused on better incorporating and further capitalizing on embedding to design panels. Figure 16 shows how embedding can be used to generate the L-shaped QRD [6].

Diffuser form-performance assignment rules – the assignment rules are limited to known panel types because they have a reliable form-performance relation. In addition to Schroeder diffusers, there are several other known and more complex types of diffusers that could be given shape

descriptions and specified in the is diffuser grammar. However, different panels used in the grammar should also perform reliably based on its particular form (form-performance relation). As the grammar expands to produce new panels and configurations ways described above, a means of validating performance will be needed. Future work should include ways to quantitatively characterize the acoustic performance of large-scale panels by investigating the appropriateness of typical metrics such as diffusion and scattering coefficients for surfaces generate by shape grammars, as well as developing computer simulations that describe the diffuse reflections. A workflow between panel/array generation and acoustic simulation should lead to new form-performance rules that can be specified by current label and weight systems to continue broadening the possibilities of this computational design method.



Figure 12. Simple computations showing aggregation and rotation rules for one-dimensional QRD panels.

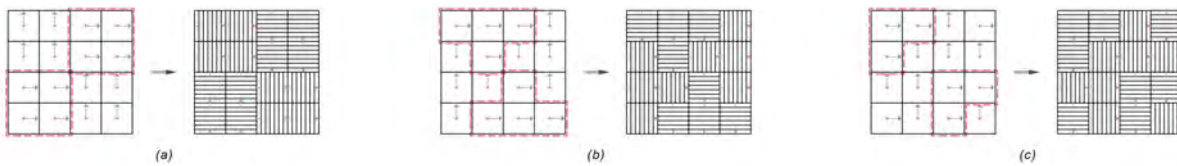


Figure 13. Examples of other small arrays of one-dimensional panels using grid-configuration rules.

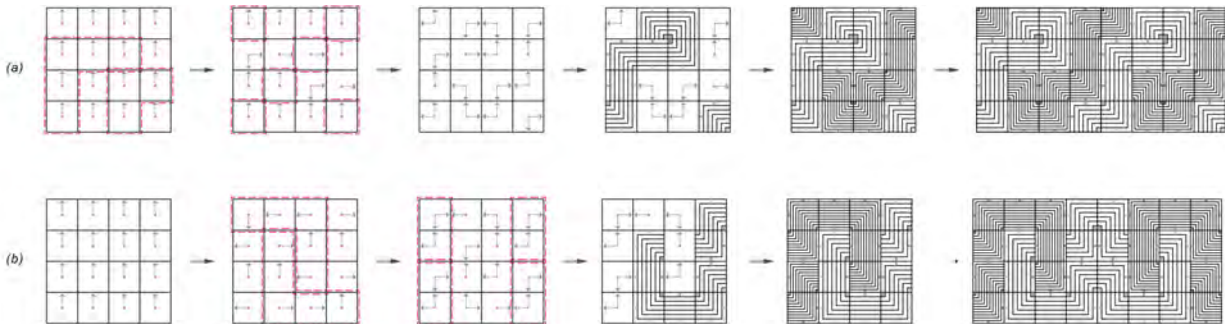


Figure 14. Computations of 4x4 arrays using one and two-dimensional panels, and varying well-counts.

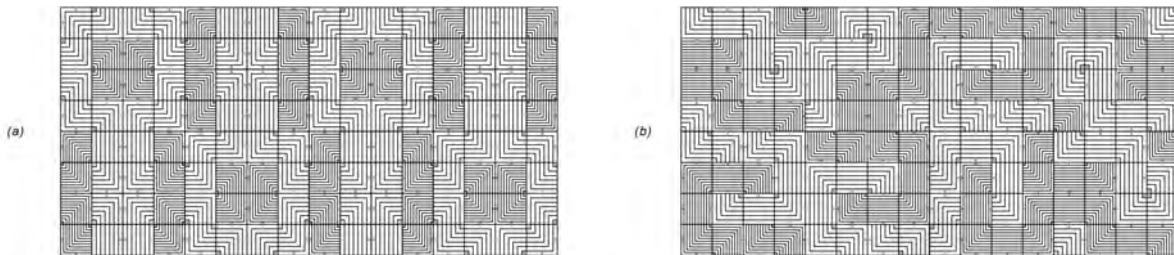


Figure 15. Two possible designs for large QRD arrays in the same language.

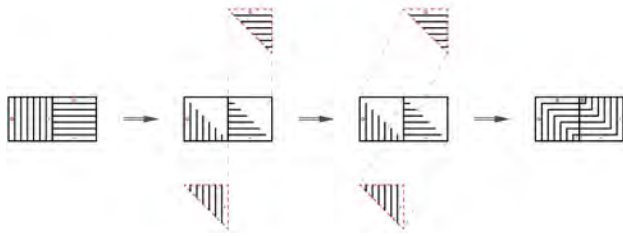


Figure 16. Example of how embedding notion can be applied to generate designs of known panel types.

7 CONCLUSION

The shape grammar proposed here uses form-performance coupled shape-rule schemata to generate aggregations of known Schroeder diffuser shapes to demonstrate how old habits in diffuser deploying techniques can be broken. Most diffuser design is limited to considering single panels using known equations that give known forms. Individual Schroeder diffusers are designed parametrically based on the number of wells and the design frequency, that produce the characteristic stepped section. These variables, which define form-performance relations of Schroeder diffusers, are specified in the grammar according to a system of weights and labels to associate designs of diffusers with their shape representation in the grammar. Generating QRD arrays with this methodology is neither mechanical nor deterministic, and can produce new and visually surprising diffusion arrays that perform reliably according to the equation that generated the individual panels.

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IMAGE CREDITS

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