ABSTRACT

This paper examines the morphology of sintered ceramic for its ability to reflect sound. The principal objective is to formulate a series of acoustic samples and to test how the different fractal surfaces reflect different frequencies of sound. The goal is to be able to qualify the effectiveness of the surfaces and to make more informed choices during the design process. The design research is based upon the extrapolation of the analog material behaviors that are based upon a novel ceramic process. The process has been replicated using digital tools and fabrication techniques. The techniques that will be discussed involve the development of code to replicate the self-organizing fractal properties that can be produced using a sand pile model along with the preparation of samples to obtain their scattering and diffusion coefficients.
INTRODUCTION

It is generally accepted that the acoustic performance of a space is enhanced through inconsistencies in the walls and ceilings. The degree to which these protrusions occur in an existing concert hall is classified by the Sound Diffusivity Index (SDI). This is typically determined through a visual analysis of drawings and photographs. Architectural objects, such as coffers, pilasters, sculptures and ornamentation play a considerable role in determining how sound is reflected. The highly ornate Grosser Musikvereinssaal, in Vienna Austria, is an example where the sound is diffused by the ornamentation. Built in 1870 by von Hansen, it is world renowned for its acoustics and minimal use of wood. Because there has been a shift toward smooth, modern hall interiors that do not employ these types of objects, the SDI is often augmented by the addition of acoustical diffusers, called diffusing sound fields. These panels typically take the form of panels that help scatter the sound. From a design perspective, these panels help reduce acoustic glare, but they are traditionally conceived of as secondary elements to the architecture. The research outlined here seeks to recast the architectural interior and the SDI not as discrete criteria but as equal parts in the design of an integrated architectural solution. This includes the design of the space and the unitary design of the walls ceilings and soffits using ceramic. Peter D’Antonio has pioneered research in the field of sound diffusion and David Bradley is developing research related to the fractal dimensions of rough surfaces. Work in this field is relatively new and multidisciplinary, bringing together researchers in physics, acoustics, mathematics, and design. With these advancements, the opportunity exists to develop a new form of architectural synthesis between the space, the acoustics and the materials that can allow for a greater degree of variation and articulation.

RESEARCH OVERVIEW

The research outlined here seeks to recast the design of the concert hall interior, its ornamentation and its acoustical performance not as discrete criteria, but as equal parts in the design of an integrated architectural experience using ceramic. This work has been prepared in conjunction with Assistant Professor David Bradley Ph.D., specialist on the acoustics of rough surfaces, Vassar College, Katrin Mueller-Russo, Industrial Designer, Pratt Institute and Farzin Lotfi-Jam, who was instrumental in the development of the script to replicate the features of the granular ceramic. The work discussed in this paper consists of two phases.

Phase I involved the fabrication of ceramic prototypes, initiated at the European Ceramic WorkCenter (EKWC) in 2010. A technique was developed to sinter granular porcelain into reliefs without the use of molds (Figure 1).

Phase II involved the preparation of nine samples to test how they interact with reflected sound. The tests were carried out by David Bradley Ph.D. at Vassar College. The goal was to obtain the scattering coefficient and the diffusion coefficient from the samples shown in (Figures 12-14).

These two phases anticipate future work involving the design, implementation and analysis of the tiles in a concert hall setting.

PHASE I SUMMARY: HEAP TILES CERAMIC PROTOTYPES AND ANALOG COMPUTATION

To minimize environmental impact, acoustic treatments need to be made from sustainable materials. Ceramic clay is a resource that is natural, inert, plentiful and reusable. Porcelain and other combinations of reusable calcined clay, such as Molochite, were test fired in 2010 at the European Ceramic WorkCenter (EKWC). Calcined clays are commonly used as aggregate or grog and are rarely explored as a finish material. Similar results were achieved using a variety of clays, but the strongest bonds and sharpest fidelity were achieved with spherical porcelain grains. Efficient manufacturing processes have been developed that allow the material to self-organize once the grains begin to flow under the force of gravity. No molds are required and an unlimited set of unique tiles can be achieved. There is minimal waste and the overflow material can be collected and reused. Green power can also be used to power the electric kilns during firing.

To better understand the objectives of the generative methodology and the tooling requirements in the digital environment, it is necessary to provide a brief summary of the ceramic work in Phase I. The Phase I prototypes were fabricated using a technique of draining spherical porcelain grains through a perforated porcelain plate to produce surfaces, or heaps. The morphology of the peaks and valleys and the porosity vary due to the increased presence of holes (Figure 1). Under the force of gravity, the grains self-organize into a three dimensional surface. The formation, along with the porcelain plate, is then fired to produce a sintered surface that preserves the formation as a monolithic heap. The sintered tile is subsequently glazed to make it less pervious to moisture. Any formation can be consistently repeated. For any chosen two-dimensional pattern of holes, an identification results in three-dimensions. A variety of prototypes were achieved in the form of tiles with flat (LT series) and curved surfaces (CT series). The heaps take two distinct forms, the first type is referred to as the positive surface and it collects on top of the surface of the plate (Figure 5). The majority of this formation is characterized by conical depressions with concave curvature. A second heap forms as the grains pass through the holes in the tile and are
deposited below on a flat surface. This type of formation is referred to as the negative surface, and in this instance the formation is characterized by ellipsoidal mounds with convex curvature. Because the convex mounds are more massive and less consistent, they were not produced in ceramic. The opportunity to consider the negative surface was reintroduced only after the tiles were generated computationally (Figure 4). While it is possible to compute the negative surface, it is not possible to manufacture them using the same ceramic process. The negative surfaces do not have undercuts and they can be produced in ceramic using molds. Because of this fabrication constraint, the positive surfaces were selected for the first round of acoustical tests.

PHASE II CUSTOMIZED SOFTWARE TOOLS

This portion of the work was focused on developing architectural parts based upon reproducing the analog behavior of the granular ceramic. The demands of the acoustical tests required an increased level of control over the morphological variation and the mass production of parts that far exceeded what could be achieved with the analog prototypes. The implementation of the script saves considerable resources while increasing the number of tests that can be run and the number of parts that can be output.

In order to replicate this behavior digitally, a Python script was developed. The script makes it possible to explore the correspondence between three discrete and variable forms of information: the surface morphology, the porosity of the surface, and the tile boundary or outline of the base mesh. Once the script was developed, the term hole was replaced by the term attractor. With these inputs the tool provides a means to test, visualize and output different degrees of fractal behavior. The script makes it possible to move from a two-dimensional data set to a corresponding architectural object that adheres to the morphological characteristics of the ceramic heaps without repeating the work in ceramic. The test samples could not have been produced without this tool.
There were other design benefits. Rapid prototyping makes it possible to capture both the convex and concave sides of the surface in a single model. This was not achievable during the analog process. With some of the digital tests, the output included curvatures and slopes that could not be achieved using the sintering process. Some of these anomalies or errors have also resulted in useful alternatives (Figure 2). The digital prototypes have also raised the possibility that alternative methods for forming the ceramic could be employed to produce thin shell units alongside the sintered units. Thin slip cast surfaces can also be cold formed during the drying process and have the added benefit of being translucent when made in porcelain (Figure 3). The sintered units are very dense and heavy. This process could also provide a means to alter the wall thickness and the transmission values; however, hollow units were not pursued during this phase of work.

**PHASE II TESTING FOR SPECULAR AND DIFFUSE SOUND**

When sound hits a surface, it can do one of three things: transmit, absorb, or reflect. In an acoustically sensitive room, the reflected sound is the probably the most important since that is what we hear. Sound reflects off of the surface in one of two ways, specularly or diffusely. A specular reflection is one in which the angle of incidence is equal to the angle of reflection (Figure 6). A diffuse reflection is one in which the angle of reflection is totally independent of the angle of incidence. There are two standard coefficients that characterize acoustic scattering: the scattering coefficient and the diffusion coefficient. Each quantity is used to analyze and quantify the scattering phenomenon in different ways and each test requires different spaces: a reverberation chamber for scattering and an anechoic chamber for diffusion.⁴

The scattering coefficient is the ratio between the sound that is not reflected specularly and the total reflected energy. This ratio gives an indication of how much sound is reflected away from the specular direction. The scattering coefficient is useful in computational acoustics room modeling, and gives a general indication of how the reflected sound behaves.⁵

This diffusion coefficient tells us how uniformly the sound is reflected from a surface. Unlike the scattering coefficient, the diffusion coefficient is very difficult to measure. It requires a device known as a 3D Acoustic Goniometer, shown in (Figure 9). The goniometer is made up of a sample stage connected to a rotating semi-circular microphone array. A loudspeaker is used to irradiate a reflecting surface that is placed on the sample stage, and the microphone array is rotated by five-degree increments. When the rotation is complete, the reflected sound has been measured.
over the entire hemisphere above the surface. From the data, the diffusion coefficient is calculated. It's a time-intensive and complicated measurement, but it tells us a lot about the behavior of the surface, which helps designing acoustically sensitive spaces like concert halls and recording studios. This whole measurement must take place in a special room called an anechoic chamber, which is a large room lined with sound absorptive wedges (Figure 9). The absorptive wedges ensure that errant reflections from the surfaces of the room do not interfere with the reflections being measured from the surface. These measurements are also made for several angles of incidence.

There are several test parameters that were involved in designing the samples. The first constraint involved matching the design of the samples to the forty inch, circular turntable. The second constraint requires that the sample consist of the same unit so a reliable value for the diffusion coefficient can be obtained. For this reason the samples consist of repetitive tiles. The primary benefit of the ceramic technique is its ability to produce unique tiles. Once individual coefficients can be obtained, the tiles can be mixed more reliably during simulation. The last factor concerns the scale of the test, which was conducted at quarter size (Figure 8). Roughly sixty-five units comprise each forty inch sample. The 60cm ceramic unit (15cm model) is based upon the manufacturing limitations of the previous ceramic prototypes. The use of molds was introduced solely to expedite the fabrication of the test samples and it is not intended to replace the ceramic sintering process. Since absorption was not considered, the samples could be made from any rigid material. Each unit was generated using Python in conjunction with Rhino. The resulting meshes
were 3D printed, sealed and rubber molds were made (Figure 11). Solid versions of the prints were cast in plaster to construct the test surfaces (Figure 10).

PHASE II COMPUTATIONAL DESIGN AND ROUGHNESS

There is a strong interest in using the fractal surfaces to diffuse sound. In designing the tiles, it was necessary to rigorously assess the morphological features that contributed to the roughness of the surface profile. A comparison between the three tiles in the M and D families can be seen in (Figure 7). The design parameters that contribute to the presence of arced segments in the section are tightly integrated and the majority of the parameters belong to the size, outline, and orientation of the holes in the base tile.

More holes or attractors typically result in rougher curves with more segments. The remaining parameters pertain to the number and relative positioning of the holes and their proximity to the boundary of the tile. For this reason, questions related to the roughness of the surface profile were given lengthy studies. During the process of making the analog tiles, it became evident that the mathematical character of the heap was complex. The granular flow of material in the analog surfaces produced distributions nearly identical to a Voronoi tessellation employing the same centroids. During Phase II, the mathematical relationship between the surface area of the heap, its volume and the number of holes was measured. A series of tests were conducted to compare the surface area of the heap to its volume. With the analog models, the angle of repose (the angle of heap once it comes to rest) preserves a constant slope, roughly forty-five degrees, from any
open boundary. The measurements from the digital models revealed that the volume of the heap is consistently 1.41 times larger than the initial surface area of the tile, regardless of the number of holes present in the initial surface. In mathematical terms, increasing the number of holes increases the length of the boundary. This has been demonstrated by Mandelbrot’s analysis of the length of coastlines. However, given this relationship, more holes do not necessarily prove to make a rougher surface. In extreme cases, such as tile D3, where there are many evenly distributed holes, the result more closely resembles noise.

TEST TILE FAMILIES

Three morphological families, consisting of three hexagonal tiles each, were tested for their ability to scatter and diffuse sound. Ten sample surfaces were produced, each one containing identical tiles. The tenth surface consists of identical flat tiles that served as a control surface. One advantage of the surface morphology is its ability to diffuse sound hemispherically. The general design strategy was to see if multiple frequencies could be diffused by a single tile rather than assigning individual frequencies to individual tiles. Each family is designed to include a range of amplitudes and depths that can be compared in order to help identify which frequencies of sound are diffused. Since this phase of tests is focused on the scattering of the sound, the holes were closed to eliminate absorption. The term attractor was adopted due to its behavior in the construction of the Python script as a means to replicate the dispersal of the grains during the analog process. The shape of the attractor in each family is either a circle or an oval.

FAMILY I SMALL AMPLITUDES: TILE D1, D2 AND D3

The first family (D1, D2, and D3) contains the most uniformly rough surfaces (Figure 12). A base pattern of circular attractors was established to control the sampling of the depressions. As more attractors are introduced, the surface area of the tile decreases and the amplitude between the convex depressions decreases. This was managed by varying the density and number of attractors accordingly, 36 attractors for D1, 108 for D2 and 180 for D3. The process of adding attractors
in this family occurs by randomly choosing the nearest neighbor. The roughness was established by the irregularity in the pattern of attractors with tile D2 containing both of the large and small amplitudes that are present in D1 and D3. The theoretical principal guiding this series is based on establishing a self-similar set of depressions on the surface and to determine if a wider range of conical depressions can have an effect on a greater number of wavelengths.

FAMILY II LARGE AMPLITUDES:
TILE M1, M2 AND M3
The second family of tiles is characterized by an asymmetrical arrangement of large islands (Figure 13). The attractors are arranged along fronts or boundaries that generate valleys between the large islands. The roughness of the surface was altered largely through the spacing and alignment of the oval attractors. This family has the largest draw depth, almost double the depth of family I (11.35 cm for M2 and 6.78 cm for D1). As a family, the M series contain the largest islands and the most uniformly articulated valleys. The theoretical principal guiding this series is to devise the deepest formations and to populate the coastline of the larger islands with both regular (M1) and irregular (M3) sequences of conical depressions.

FAMILY III SYMMETRICAL AMPLITUDES:
TILE R1, R2 AND R3
The last family of tiles is characterized by a symmetrical arrangement of ridges and valleys (Figure 14). Unlike the other two families, they have a pronounced directional bias. Each tile has been designed with different frequencies and number of ridges: three in R1, four in R2 and five in R3. Fewer frequencies result in larger depressions with a greater draw depth, the largest depth of 9.8 cm exists in R1. The roughness in the valleys increases as more attractors are placed along the base of the valleys. The theoretical principal guiding this series is to design large symmetrical waves that are populated by a series of smaller scale waves with increasingly smaller frequencies. While these tiles do produce hemispherical reflections, they are more similar in their organization to linear diffusers.
SUMMARY

The Phase I tests have only tested for reflected sound. Absorption and transmittance have not been tested. The first round of tests that were conducted to obtain the scattering coefficients is unusable due to the incorrect temperature and humidity levels inside the chamber. The data for the diffusion coefficient is incomplete and has not been processed. In order to proceed to the next phase of work, values for both coefficients will be assumed so that the architectural design work and analysis can proceed.

CONCLUSION

There are many questions that remain open for investigation regarding the tiles. Because of the holes, the material can also be employed for purposes of absorption. The potential to deploy the perforated units, with the holes open, as acoustic absorbers, and lighting, is an interesting capability that needs exploration. The possibility of introducing a more varied set of ceramic processes that can address transmission using solid or hollow units holds promise when coupled with other architectural requirements.

The question remains whether or not the small scale convex or concave curvatures that arose during the rapid prototyping phase will affect the diffusion differently. Regardless, the opportunity exists to scale up the convex surfaces inside the volume and to use them to reflect sound at larger scales. There are three areas or scales for investigation that will be pursued in the next phase as the process is extended to take on the hall design. The largest scale is the definition of the architectural volume of the hall itself using the surface morphology. The second scale pertains to the design of the middle scale of the room. How can the morphology be used to refine the surface diffusivity index (SDI) of the ceiling and walls as the need and location for more acoustic differentiation is pinpointed in the design process? As other scales of the design are developed, the opportunity exists for the fractal approach to become more layered in the design of the surfaces. The smallest scale of diffusion involves the tessellation and patterning of the space into discrete tiles, and this affords the opportunity to produce a larger palette of tiles that are not restricted to the parameters of the tests, but to the versatility of fabrication process.
NOTES


3. “The side walls are made irregular by over forty high windows, twenty doors above the balcony, and thirty-two tall, gilded buxom female statues beneath the balcony...Less than 15% of the interior surfaces is made of wood. Wood is used only for the doors, for some paneling around the stage, and for trim. The other surfaces are plaster on brick or, on the ceiling and balcony fronts, plaster on wood lath.” (Leo Beranek (2004) Concert Halls and Opera Houses: Music Acoustics and Architecture (New York: Springer-Verlag. 173).


5. David Bradley, e-mail message to author, July 3, 2014.


8. “Fractal mathematics is used to create natural objects in computer generated graphics, for example to make landscapes for animated films. Fractals are surfaces with a different visual aesthetic compared to common sound diffusers and so offer the possibility of expanding the pallet of surfaces available to designers. There is reason to believe that fractal surfaces may have good acoustic properties. Fractals are self-similar or self-affine; as a surface is magnified a similar looking surface is found. Consequently the rough surfaces at different magnifications can be used to scatter different frequency ranges...” (Trevor J. Cox, & Peter D’Antonio (2009) Acoustic Absorbers and Diffusers: Theory, Design and Application (New York: Taylor and Francis, Second Edition. 364).


REFERENCES


Bradley, David. 2014. e-mail message describing specular and diffuse sound.


IMAGE CREDITS

Figure 1. Sayers, Nathan (2010) Heap Tiles.

Figure 2. Russo, Rhett (2013) Digital Heap Tiles.

Figure 3. Russo, Rhett (2013) Lumascape.

Figure 4. Russo, Rhett (2013) Digital Heap Tiles.

Figure 5. Russo, Rhett (2013) Geometric Normal Analysis.

Figure 6. Russo, Rhett (2013) Racycasting Diagram.

Figure 7. Russo, Rhett (2014) Digital Heap Tile, overlay of section profiles.

Figure 8. Russo, Rhett (2013) Quarter scale acoustic mockup.

Figure 9. Bradley, David (2013) 3-D Acoustic Goniometer.

Figure 10. Russo, Rhett (2013) Casting and drying.

Figure 11. Russo, Rhett (2013) Digital Heap Tiles, molds.

Figure 12. Russo, Rhett (2013) Family I D Series.

Figure 13. Russo, Rhett (2013) Family II M Series.

Figure 14. Russo, Rhett (2013) Family III R Series.

RHETT RUSSO received his Masters of Architecture from Columbia University; he is an Associate Professor in Architecture at NJIT and partner at Specific Objects. Rhett has received numerous awards: the SOM Fellowship, the Van Alen Institute Dinkeloo Fellow at The American Academy in Rome, and the Young Architect’s Award from the Architectural League of New York. He is the recipient of research residencies at the European Ceramic Workcenter, where he combines digital technology with ceramics. His work has been exhibited internationally, at the Beijing Biennale, and his writing has been published in Matter: Material Processes in Architectural Production and Meander: Variegating Architecture.