euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Generating Complex Reflective and Diffusive Geometries through Parametric Design

Laura C. Brill[1], John T. Strong[1], Scott D. Pfeiffer [1], Marcus R. Mayell [1]

[1] Threshold Acoustics LLC, Chicago, USA
corresponding author: lbrill@thresholdacoustics.com

Abstract
The implementation of parametric tools demands careful optimization to ensure that input parameters align with design performance objectives. Two case studies are presented to demonstrate Threshold's range of uses. In one example, an architectural vision for a rectilinear flexible performance space called for a ceiling reflector array of concentric spaced rings. In a three-dimensional computer model, parametrically generated geometries were defined and used with raytracing and mapping techniques to tune array coverage while directly adjusting its spatial characteristics. In another example, an aesthetic vision was translated into geometric parameters used by a genetic algorithm to optimize acoustic diffusion performance. Finite-difference time-domain analysis was used to evaluate fitness of each design candidate within the genetic algorithm.

Keywords: FDTD, Genetic Algorithm, Parametric Design, Ray Tracing, Architectural Acoustics

1 Introduction

One of the primary challenges of acoustic consulting is to evaluate the anticipated behavior of design directions proposed by the architect, and offer constructive feedback to allow designs to advance as required by the project schedule. Frequently, this requires the evaluation of multiple options or sequential iterations in a short amount of time. While current computational acoustic analysis tools are quite powerful, the ability to run many iterations quickly or simultaneously is not always possible without a substantial outlay of time to setup analyses and to gather and collate results into a coherent data set. The advent of parametric modelling tools and methods offers alternative possibilities for acoustic evaluation of larger sets of options in shorter amounts of time. Here we discuss two case studies where parametric modelling and analysis were used to respond to such needs.

2 Gonzaga

The Myrtle Woldson Performing Arts Center at Gonzaga University in Spokane, Washington, is a multi-venue performing arts center that completed construction and opened in 2019. One of the venues, the Martin and Edwidge Woldson Recital Hall, is a 168-seat recital hall that makes use of a set of deployable tiered seating for end-stage recital configurations, which can be retracted to create a flat floor condition for large ensemble and dance rehearsals. This combination of uses was established early in the design process as a requirement for the successful function of the facility.

A recital or other end-stage function in this room requires strong, consistent, and equitable distribution of overhead reflections of performers to all members of the audience seated in the tiered seating as well as across the performance area. Likewise, when used in a flat floor condition for rehearsals, equal distribution of overhead reflections is important so that cross-ensemble hearing conditions are good. A typical approach for accomplishing these goals is to locate an array of acoustic reflectors in the ceiling space a distance below the structural lid. Typically the reflectors take rectilinear shapes, and the array is sized and spaced equally and symmetrically to ensure the reflection behavior is not "biased" in one orientation as compared to any other.

At Gonzaga, the architect sought a visual character for the reflector array that was not gridlike and symmetrical, in part because the floor plan of the room was not symmetrical. Their vision was to use an circular array consisting of a central circular reflector with a series of concentrically located larger rings, with sufficient gaps between each successive ring to allow lighting, HVAC supply, AV device rigging, and other building systems to be located. A rendering showing the design concept is seen in Figure 1 below.

Figure 1 – Rending of Gonzaga Recital Hall ceiling

Because of the sizes of gaps required in the array, the sectional profile of each reflector would need to be radiused to spread sound reflections across a wider area and avoid the "striping" phenomenon seen with flat reflectors. The result would be a central circular reflector with a spherical "bulge" and rings with a bulge in the radial direction resulting in a truncated toroidal shape.

Raytracing is a frequently used technique to determine the shaping of a curved reflector. However, in this case, a simple two-dimensional raytrace would not be sufficient because of the complex three-dimensional relationship between any source or receiver position and different portions of the reflector surfaces. Additionally, the potential for unforeseen and unwanted overlap or focusing conditions would be high if only analyzed in two dimensions. Therefore, a form of analysis that would allow three-dimensional raytracing as well as evaluation of the relative intensity of the reflected sound field through the room would be necessary.

Threshold maintains a set of tools in the Rhinoceros modeling program and its accompanying Grasshopper module (both available from McNeel and Associates) that enable raytracing in three dimensions. Grasshopper offers modules for mathematical calculation as well as generation and truncation of three-dimensional geometries that may accept calculation results as parameters. This allows surfaces and other geometries to be defined directly by their geometric parameters (such as size, X,Y,Z coordinates within a room, radius of a curved surface, angle of inclination, etc.). Additionally, the Pachyderm toolset, supported by ORASE (Open Research in Acoustical Science and Education), offers a raytracing module that calculates the angle of reflection of rays sent from a given source point off of an object under study. By linking all of these modules together, it is possible to vary the geometric parameters of a reflector object and review the resulting impact of coverage characteristics in near-real time. This workflow was determined to be the most easily tunable and comprehensive way of analyzing the general behavior of a complex the reflector array.

The decided approach was to take user input of some array parameters – width of each reflector, width of each gap, and "bulge" radius of each reflector – and construct the array in three dimensions with those parameters. Simultaneously, rays were sent from a movable source location to all reflector surfaces, and the first-order reflections off of the array would be mapped to a listener plane corresponding to either the flat-floor condition or the tiered seating condition. The ray density reaching each reflector was set to be equal, so that any "clumping" or uneven distribution at any point in the listener plan would represent a "hot" spot receiving more reflected energy than other locations.

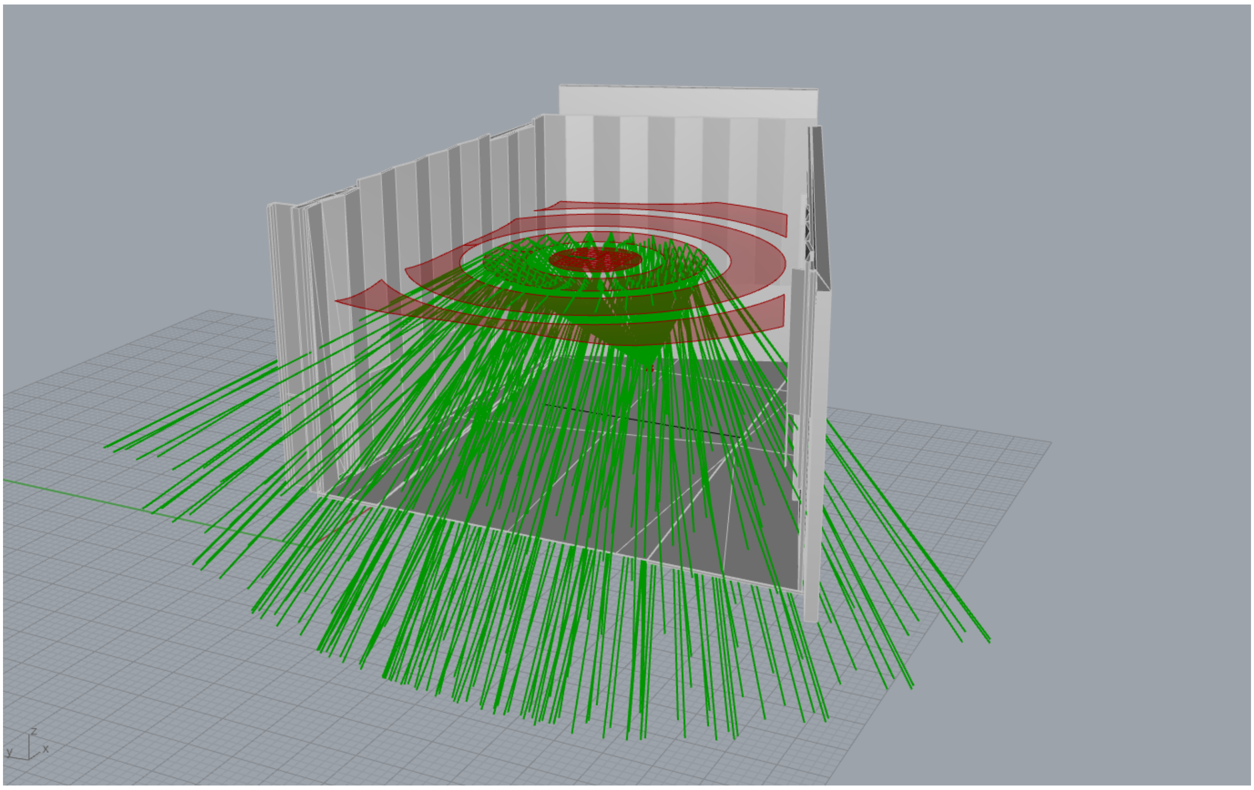

Figure 2 – First-order reflection distribution from a single ring element

As a result, the parameters of each reflector and the source position could be changed dynamically, and the resulting reflection distribution would be updated at the listener plane. Parameters were tuned for as even distribution as possible for a given source location and listener plane, and then the distribution checked for evenness for another source position and/or listener plane. Array parameters were set as final when an equally even distribution resulted for a widely varying set of anticipated source locations based on the room's intended functions.

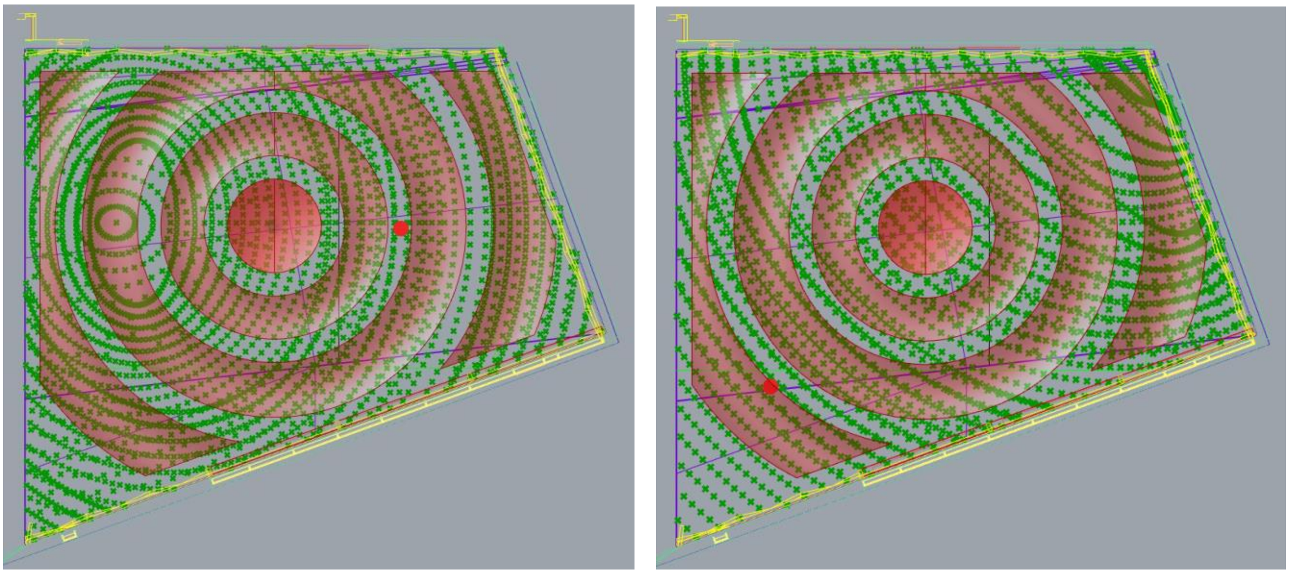

Figure 3 – First-order reflection hits on audience plane from entire array; ray source location in soloist position (left) compared to ray source location in far ensemble position (right)

3 Project T

Establishing the acoustic goals and subsequent design of the perimeter walls of theaters and concert halls takes thought and consideration; doing so for a multipurpose space with multiple configurations requires perhaps even more careful analysis. In this theater, reconfigurable multi-tiered seating towers and floor seating will be used to create multiple stage types: proscenium, thrust, and in-the-round. In all of these configurations, the acoustic goal is the same: provide true and strong early energy to all audience members, while randomizing the later energy.

To accomplish this, two acoustic goals were set during design: surfaces that are closest to the audience (the walls of the seating towers) and other critical first order reflection surfaces should be solidly backed and reflect specular, coherent wavefronts, while perimeter wall surfaces should contribute diffuse energy to the late portion of the room's response while avoiding late specular returns to the stage. By nature of the configuration, the perimeter walls would have airspace behind them, which presented an opportunity to further increase their diffusive nature.

During the early portion of the design process, the architect had an aesthetic preference for a panelized solution made up of a set number of fluted planks. There were a few fixed parameters: number of planks, overall panel dimensions, the edge condition of the panel and planks (fixed offset from Unistrut, fixed radius at edge so the planks would always match when grouped), etc. There were many variable parameters: plank spacing, number of unique planks, ordering of unique planks, number of flutes, radius of flutes, position of flutes, etc. The solution space was large.

A traditional approach may have involved the creation and acoustic testing of scale mockups of a few of the architecturally desirable solutions, with the final design chosen from one of those tested candidates. However, in addition to the time and expense associated with the construction of scale mockups, this approach would have severely constrained the exploration of the solution space. By utilizing finite-difference time-domain (FDTD) analysis within a genetic algorithm, a larger than conventionally possible portion of the solution space was able to be explored.

3.1 Implementation of FDTD

FDTD is a numerical technique that can be used to simulate the wave-based behavior of sound propagation by calculating a discretized form of the wave equation. FDTD has its roots in simulating wave propagation and scattering in electricity and magnetism, and has been utilized by the acoustic community to simulate acoustic wave propagation, reflection, and scattering [1]. FDTD differs from most conventional acoustic analysis tools, which use ray tracing to simulate the particle-like behavior of waves. Ray tracing is an effective technique, especially at high frequencies, but does not accurately capture diffraction and scattering behaviors of sound waves.

The advantage of FDTD's ability to simulate sound propagation more accurately can come with a high computational cost. While many researchers are exploring more advanced techniques that make the possibility of simulating entire rooms in real-time a likely outcome, we implemented a simpler, 2D FDTD scheme that allowed comparison of relative differences between simulated specimens. This 2D FDTD scheme calculates the wave equation using a leap-frog scheme on standard-rectilinear (Cartesian) grids.

To mimic the evaluation procedure typically used in an anechoic chamber for physical mockups, the geometry under evaluation required a simulation domain with free field behavior. This was accomplished by bounding the simulation domain with Perfectly Matched Layers (PMLs) to absorb all incident energy at the perimeter [2]. The geometry under evaluation was simulated as perfectly reflective; thus the result of comparative analysis provided insight into the scattering behavior of the geometry alone, without the effects of the substrate's material properties. The simulation domain was treated as air at standard temperature and pressure.

An impulse response was simulated by exciting the simulation domain with a 2D omnidirectional Gaussian pulse at a predetermined source position and recording the resulting pressure response over time at specific, pre-determined nodes. The simulation set up is shown in Figure 4. Discrete spatial and time steps were chosen to stably resolve the highest frequency of interest by satisfying the Courant criteria. Because of the computational cost of FDTD, the frequency range of interest was limited as much as reasonably possible to lessen the nodal density required to satisfy the Courant criteria but was typically up to 11,000 Hz. Additionally, GPUs were used to speed up calculation time. All analysis was conducted using MATLAB (MathWorks, Natick, MA).

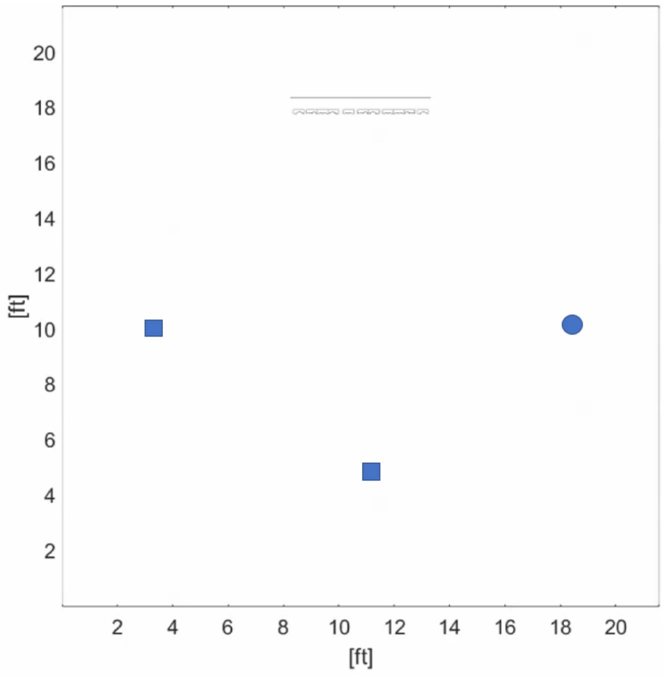

Figure 4 – Sample of the FDTD simulation setup. The circle depicts the location of the source and the squares depict receiver locations.

3.2 Genetic Algorithms

Genetic Algorithms (GAs) are an algorithmic technique used to search for an optimum configuration in a set of parameters without the need to test all possible configurations by attempting to mimic the process of biological evolution [3]. For this project, GAs were developed to optimize the panel profiles for the desired acoustic diffusion characteristics while working within the aesthetic constraints set by the architect. The GA was implemented by generating a set of governing parameters to encompass all possible acceptable architectural configurations for an acoustically diffusive wall panel. Each parameter is said to represent a "gene;" a given combination of genes comprises a "chromosome" that represents the traits of each panel. Binary coding was utilized to represent the genes and chromosomes.

This GA started by generating a population of viable chromosome candidates. Each candidate was then tested using FDTD. Next, the fitness of each candidate was calculated; that was then used to determine the next generation of the population. The next generation retained the best performing candidates of the previous generation and then used fitness proportional selection to determine which candidate would produce offspring; offspring were produced using single-point crossover. Mutations were also introduced at a specified rate to introduce variety into the genetic pool. The steps were repeated until the best candidate persisted for a specified number of generations meaning that the solution had converged. This process is depicted in Figure 5.

The fitness of each candidate was determined using a heuristic to evaluate diffusion. The fitness function was written to minimize the differences between the slopes of the frequency responses of a tested panel and a reference reflector (a flat panel) without penalizing for level differences as well as minimize the difference in dynamic range of the tested panel compared to the specular reflection of the reference panel response.

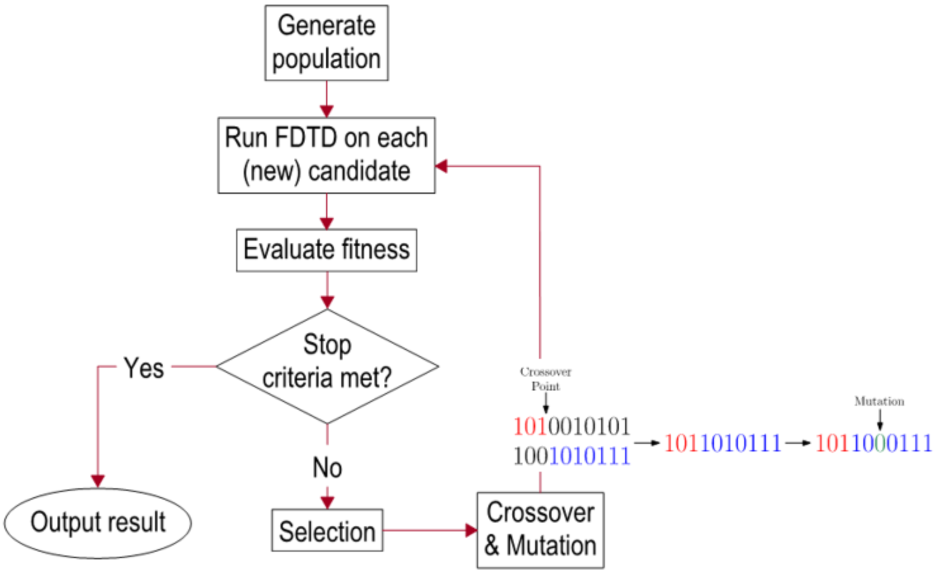

Figure 5 – Flow chart showing Genetic Algorithm process and crossover and mutation technique.

3.3 Discussion

In order to write the GA, all of the geometric parameters needed to be defined and translated into mathematic expressions. Even before acoustic analysis took place, geometric parameters were refined to limit the size of the solution space and meet the aesthetic goals of the architect. The refinement process took time. Once the architectural team and the acoustic team were satisfied that the algorithm would only return candidates that were aesthetically acceptable, we ran the genetic algorithm to optimize the acoustic performance. The entire process took months, but the genetic algorithm coupled with acoustic simulation allowed us to evaluate exponentially more panel candidates than would have been possible or reasonable with physical mockups.

4 Conclusion

The two given project examples demonstrate a use of computer-based methods to derive and evaluate acoustically driven architectural designs. In both cases, the demands of iterative architectural vision required quick action on the part of the acoustic designers to meet fast-paced project schedules. While every project requires some adapting of methods to suit a specific application, some cases will require more effort and time to meet a given architectural vision. The nuance, complexity, and number of iterations of an architectural vision coupled with the constraints of tools, fee, and schedule all impact how detailed acoustic analysis and feedback can be; thus, the capability of such computational methods to return relatively comprehensive analyses in widely varying applications in a comparatively quick timeframe brings a dramatic increase in the range of possibilities than can be evaluated. While there is more improvement to make, the current abilities of these tools to fit within the consulting framework elevates the performance and visual design potentials in each of these project examples.

It is within this context that intuition and calculation are held in close tension. If a tool is not readily adaptable for a given application, or project timing does not allow for its use, a more intuitive approach may be required. For example, while greater definition of grid response and analytical feedback would be useful in the Gonzaga example, project timing would not have permitted such granular analysis, nor the development or deployment of tools to accurately predict these metrics. In cases like these, value judgements are made based on experience and a keen knowledge of the limitations of the calculation method used to evaluate the acoustic behavior. For projects like Project T, a more rigorous method of evaluation including physical mockups can be conducted to verify the intuitive decisions made during the design process.

The success and value of the process deployed are often directly related with the ability of these methods to quickly interface with the architectural design process. Tools such as Grasshopper exist within a realm (Rhino 3D modeling) that the architectural design community are already adept at interacting with – the sharing of models and geometric ideas can be passed between offices with ease. Other tools require adaptation to meet the specific design function. These tools can serve an iterative design process well, once the parameters of the architectural vision are well defined.

Acknowledgements

The authors gratefully acknowledge the members of the design teams on both projects as well as our colleagues at Threshold Acoustics.

References

[1] Cox, T.; D'Antonio, P. *Acoustic Absorbers and Diffusers: Theory, design and application*, Taylor & Francis, London (UK), Second edition, 2009.

[2] Yuan, X.; Borup, D.; Wiskin, J. W.; Berggren, M.; Eidens, R.; Johnson, S. Formulation of Berenger's PML Absorbing Boundary for the FDTD Simulation of Acoustic Scattering. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol 44 (4), 1997, 816-822.

[3] Holland, J. H.; *Adaptation in natural and artificial systems : an introductory analysis with applications to biology, control, and artificial intelligence*, University of Michigan Press, Ann Arbor (USA), 1975.