

15 to 17 September 2019 in Amsterdam, Netherlands



Improving Meeting Room Acoustic Performance through Customized Sound Scattering Surfaces

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ABSTRACT

This research project aims to improve the acoustic performance of the rectangular meeting room through the design of new architectural surface geometries. Meeting rooms are spaces of communication and therefore acoustic performance is of critical importance. Unfortunately, when designing meeting rooms, acoustics is often not considered, and even if a designer wanted to design an amazing sounding meeting room, there exists little guidance. Due to their size and form meeting rooms often suffer from flutter echoes and room resonances. Performance goals were drawn from a variety of previous studies ranging from classroom acoustics and small room acoustics. Acoustic computer simulations were carried out using ray-based geometric methods (using Odeon), and wave-based numerical methods (using a custom FDTD software). A parametric CAD model was developed to generate different sound scattering surfaces. Different configurations of acoustic absorbing and scattering surfaces were simulated and compared. The final design option was fabricated using a 6-axis robotic arm. The meeting room was measured before and after the installation of the acoustic surfaces and results were compared to simulations. This research outlines a design workflow, and acoustic performance objectives, that can be used by architects and engineers to design better sounding meeting rooms.

Keywords: Sound Scattering, Meeting Rooms, Acoustic Simulation, Digital Fabrication

1. INTRODUCTION

Meeting rooms are spaces of communication and therefore acoustic performance is of critical importance. Unfortunately, when designing meeting rooms, acoustics is often not considered, and even if a designer wanted to design an amazing sounding meeting room, there exists little guidance. Due to their size and form, meeting rooms often suffer from a variety of acoustic defects including flutter echoes and room resonances. Speech and noise levels are influenced by room acoustics. This research project studies existing meeting rooms, and as such modifications to room form were not possible, and so this project aims to improve the acoustic performance through the design of architectural surface geometries.

Kolarevic (1) has observed that "a new kind of architecture is emerging, using building performance as a guiding design principle, and adopting a new list of performance-based priorities," and that this architecture "places performance on a par with, or above form-making." The practice of architecture has shifted to the use of digital design technology, and this has meant an increased use of parametric design, building information modelling, and qualitative performance-based simulation. (2) A parametric digital model was developed using the CAD software Rhinoceros and different sound scattering surfaces were generated. Acoustic computer simulations were carried out using ray-based geometric methods and wave-based numerical methods. The Odeon room acoustic software was used to perform room acoustic simulations. Scattering and Diffusion coefficients were calculated using Boundary Element Method (Reflex software). Sound wave simulations were carried out using a custom software that implements the Finite-Difference Time-Domain (FDTD) method.

While room acoustics is usually characterized in terms of reverberation time, for meeting rooms it is important to maximize early reflections without excessive later arriving sound (3). Definition (D50), STI, and EDT were used as a measures to characterize different surfaces and surface configurations. Prior research has found that sound diffusing surfaces are "beneficial for enhancing the early arriving reflection energy" and result in achieving "more uniform acoustical conditions" (4). This

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performance-based design approach was tested through simulation, and a 1:1 demonstrator was built. Digital fabrication enables instructions to be sent directly from design software to fabrication machines, and the structuring of digital workflows has been shown to be important for facilitating design collaboration (5). The final design was fabricated using a 6-axis robotic arm. The meeting room was acoustically measured before and after the installation and results were compared to simulations.

2. DESIGN

2.1 Room 341

The John H. Daniels Faculty of Architecture moved into its new building at 1 Spadina Crescent in the fall of 2017. Originally constructed in 1875 as a seminary, the building today is a both a sensitive renovation of the historic Knox College and a spectacular new addition to the building design by Boston's NADAA Architects (6). Administration, classrooms, and meeting rooms fill the renovated southern wing, while studios and workshops fill the new northern wing. Room 341 is a small room located in older part of the building. As constructed, there was no specific acoustic treatment for the room. The room has original hardwood floors, exposed brick on the exterior wall, and plasterboard walls and ceiling. The room is used for meetings of 4-10 people and can be booked by both faculty and students.

2.2 Sound Scattering Surface Design

One of the crucial things Wallace Sabine realized through his careful study of other concert halls, was that reverberation time was not the only criteria effecting the acoustics of a space, its room geometry and surface geometry were also important (7). The Musikverrein in Vienna is widely considered to be one the best concert halls in the world, and its excellent acoustics are thought to be because of its low audience seating angle and its hard, yet geometrically complex surfaces. The hall's surface complexity is expressed at several scales: the large balconies, the mid-scale windows, doorways and statues, and the small-scale carvings and moldings (8). And it is not only concert halls that can benefit from sound scattering. A previous project by the author of a digitally-fabricated meeting room suggested that meeting rooms with sound scattering surfaces perform well – that the people that use them appreciate the acoustic qualities, and the sound scattering surfaces provide a diffuse sound field that enables good communication without seeming overly-absorptive (9). While it is commonly recognized that sound scattering is important, there is still uncertainty as to how design complex surfaces to achieve the desired acoustic performance characteristics (10).

Scattering and the scattering coefficient is the measurement of the amount of sound scattered away from the specular reflection direction. The scattering coefficient is what is used in computer simulation software, and is seen to be an adequate quantity for describing rough surfaces. Cox and D'Antonio (11) explain that the depth of the diffuser relates to the frequency of sound at which maximum sound scattering will take place. A Schroeder diffuser consists of a series of wells having the same width but different depths. The depths of the wells in a Schroeder diffuser vary between zero and a maximum depth of one-half of the wavelength of the design frequency. Along with the effect of the well depth on the scattering produced by the surfaces also the well width is varied. Prior research by the author on scattering surfaces confirmed this relationship. These studies done measuring the scattering from scale 1:10 3D prints found that the depth of the scattering surface related to the frequency, the amount of detail (width of individual element) related to the magnitude of the scattering (12).

As the diffuser was meant for a meeting room and therefore for human speech, a frequency range of scattering was thought to be in the 250-4000 Hz range. Choosing a design frequency of 2000 Hz meant that the depth of the sound diffusing surface would be about 9 cm. While a deeper surface with a lower fundamental frequency would have been desirable, the size of the meeting room and the fact that the sound scattering surface needed to protrude into the room (instead of being inset into the surface of the wall) meant that the depth was limited.

2.3 Parametric Model

A digital 3D model of the room and scattering surface was created in the CAD software Rhinoceros, see Figure 1. While the room was modelled using a standard modelling approach, the surface was created using the "computational design" plug-in Grasshopper, see Figure 2. This enabled an exploration of different parameters of the diffusing surface. Acoustic performance parameters such as depth and width could be changed, and the resulting geometry could be simulated. The parametric model was additionally useful for studying more architectural concerns, in particular the extent and

characteristics of the fade of the scattering surface geometry into the flat wall surface geometry. The 3D model enabled visual exploration of the architectural characteristics of the project, generated data for acoustic simulations, and output the geometric information for digital fabrication: 3D printing and CNC milling.

Acoustic surfaces are often thought of as discrete panels to be added after a wall or room is constructed. This constructive attitude reflects a practice in architectural acoustics where acoustic interventions are often thought of either after a building has been constructed, or at least after the building has been largely designed. Panels are then added to fix or tune the performance of the room. Rather than this additive method, this experiment proposes that absorptive, reflective, or sound scattering acoustic surfaces can be integrated into the constructive logic and architectural aesthetic of the building. In this way, the sound scattering geometry would simply emerge from the wall where needed, and recede back into the wall where not needed. It was speculated that the best place for the surface would be in the middle of the wall where sound waves from speakers could form flutter echoes between the parallel walls. The sound scattering surface has gradation along both X and Y axes. Unfortunately, due to installation difficulties we could not make the surface directly continuous, so the surface at the perimeter begins thin and flat, then builds up to be significantly wavy towards the center of the installation.

The sound scattering surface "wave" geometry, see Figure 3, constrained to a maximum depth of 95mm and minimum depth of 13mm. Instead of using a Schroeder sequence for the heights of the wells, a random sequence was used. A two-dimensional grid of points was defined, and a surface was constructed that best-fit between the random points. This created a smooth surface instead of one with clearly defined wells. It was speculated that while the smooth surface may decrease the sound scattering because of the lack of (a) defined edges creating diffraction effects, and (b) a reduction in the interference between waves; the surface may increase scattering through the angular differences that increase spatial dispersion.



Figure 1 3D model of Room 341 with Sound Scattering Surface (pink)



Figure 2 Grasshopper Visual Algorithm of Sound Scattering Surface



Figure 3 Elevation of Room with Sound Scattering Surface

2.4 3D Printed Models

Different design options of the sound scattering surface were created with the digital parametric model and four of these were chosen to be 3D printed at 1:10. The four prototypes: "Concave + Scalloped", "Convex + Scalloped", "Concave + Wavy", "Convex + Wavy", helped inform the final decision on which scheme to use for the intervention. The scale model also helped gain approval from building administration. The 3D print of the final scheme, "Concave + Wavy", is shown in Figure 4.



Figure 4 1:10 Scale Model of Room with 3D Printed Sound Scattering Wall

3. SIMULATION

In current practice, the computer simulation of room acoustic performance can be grouped into two approaches: wave-based, and ray-based (13). Ray-based techniques (also called geometric methods) can be used to simulate the aural characteristics of a space before it is built and calculate acoustic parameters such as sound level, reverberation time, and quality of speech. These techniques have been implemented, and validated, in commercially available acoustic analysis software (14). Wave-based techniques (also called numerical techniques) such as the finite element method (FEM), the boundary element method (BEM), and the finite-difference time-domain method (FDTD), attempt to solve the wave equation numerically (11). Geometric methods assume that sound travels in a straight line and its reflection from surfaces is computed using geometrical methods. These methods are largely compatible with existing CAD software and a paradigm that conceptualizes and models architecture as a collection of points, lines, and surfaces. This is perhaps one of the reasons why raybased methods dominate practice. Wave-based simulations must model the space of architecture, rather that the surface – they divide the space of the digital model into small elements or nodes. These elements then interact with each other according to laws of the wave movement phenomena. This way of modelling and conceptualizing space, modelling the negative space of the air rather than the surface itself, though much more aligned with the actual physical mechanisms of sound, is strikingly different from how architects and engineers currently model and conceptualize buildings.

The project used a variety of different acoustic simulation to predict the performance of the diffusing surface and of the room itself: BEM (AFMG Reflex) was used to simulate the sound scattering properties, a custom FDTD software was used to visualize sound wave propagation and scattering from the diffusing surface, and the ray-based simulation software, Odeon, was used to predict acoustic parameters such as reverberation time, clarity, and speech intelligibility.

3.1 Room Resonances

As this is a small rectangular room with highly reflecting plaster, brick, and wood surfaces, room resonances will be audible. Room Modes were calculated. With length, width, and height dimensions of 521 x 262 x 303 cm, the volume of the room is approximately 41 m3, and the axial modes are 32.9 Hz, 56.6 Hz, and 65.21 Hz. With the width and height measurements being very similar, it was predicted that there would be a strong resonant effect at 56-65 Hz. To deal with this, the original wall design contained Helmholtz resonators, calculated for these frequencies. Due to installation limitations we were unable to realize this portion of the design at this point. It is hoped that further installations will enable us to construct and test these resonators.

3.2 Sound Wave Visualization

The finite-difference time-domain (FDTD) method is a widely used simulation technique in many different disciplines and is becoming increasingly popular in acoustics (11). FDTD was developed in the 1960s for use in studying the electromagnetic field but first applied to acoustics in the 1990s (15). The main principle of the FDTD technique is that derivatives in the wave equation are replaced by corresponding finite differences. This method tends to be suitable for small enclosures and for low frequencies due to its computationally intensive nature; therefore, acoustic diffusing geometries are generally studied in isolation of other objects and boundaries. FDTD gives a wide frequency range with a single prediction. It uses a volumetric rather that surface meshing and can give accurate prediction of scattering (16, 17). It has been previously shown that the visualization of sound waves using FDTD techniques produces very effective results that allow an intuitive comprehension of acoustic phenomena in rooms as a way to compare options, and see the diffusion of the sound energy as a result of different geometries (18).

A digital design tool was developed using Processing, which is a programming environment that enables the creation of interactive graphics and uses a Java-like programming language. This tool produces visualizations of acoustic waves. This software currently only calculates the wave propagation in two dimensions. While the algorithm can be easily extended to three dimensions, there are two issues that complicate this. First, the computational time would be increased substantially, and as this is meant to be a design tool, relatively immediate feedback is beneficial. Second, visualizations of waves become increasingly complex in three dimensions – it is easy to represent a 2D section, but very challenging to represent wave motion in three dimensional space. The parametric model described in Section 2.3. can discretize a 2D section through the room into spatial voxels, then outputs a text file with that information that serves as input into the FDTD sound wave visualizer. This enables any geometry under consideration to be easily understood in terms of its sound scattering performance. Figure 5 shows some still images from one of the sound wave visualizations.



Figure 5

from the sound scattering geometry (bottom sequence)

3.3 Sound Scattering

To quantify the amount of sound scattering of the different geometries, the simulation software Reflex was used. Figure 6 shows four of the surfaces that were studied. Once the surface is defined the calculation is quick and the results are intuitively displayed. Unfortunately, it is not possible to import user-defined geometries, and surfaces must be individually created using Reflex' limited palette of geometric primitives. This created two problems: first, there was no way to create the correct surface geometry using the pre-defined primitives; and second, the creation of the surfaces was time-consuming as each element needed to be individually defined. The author suspects that a BEM simulation software such as this could be a very useful tool if user-defined geometries could be imported.



Figure 6 Sound scattering simulation using Reflex

FDTD sound wave simulation comparing sound wave reflection from a flat surface (top sequence) and

3.4 Room Acoustic Simulation

The room acoustic simulation software Odeon was used to predict room acoustic performance. The 3D model (Figure 1) was exported as a DXF from Rhinoceros and imported into Odeon. All geometry was placed on layers that correspond to different acoustic absorption and scattering coefficients. When the geometry comes into Odeon, it makes the assignment of acoustic properties simple and error-free. The room acoustic simulations predicted a considerable improvement for the meeting room from the installation of the absorptive panels, but did not predict improvements either in reverberation time (T30, T20, EDT) or in speech intelligibility (D50, STI), see Table 1.

Table 1

Simulated EDT, T20, T30, and Definition for four conditions:

(1) empty room, (2) diffuser-only, (3) absorber only, and (4) diffuser and absorber.

	PARAM	frequency						
		125	250	500	1000	2000	4000	8000
	EDT	0.75	0.7	1.10	1000	1.07	1.02	0000
Empty	EDT	0.75	0.7	1.13	1.29	1.37	1.03	0.7
	T(20)	0.74	0.69	1.12	1.28	1.36	1.03	0.7
	T(30)	0.74	0.69	1.12	1.28	1.36	1.03	0.7
	D(50)	0.6	0.63	0.46	0.42	0.4	0.5	0.64
Diffuser	EDT	0.75	0.7	1.13	1.28	1.35	1.02	0.69
	T(20)	0.74	0.69	1.12	1.27	1.34	1.02	0.69
	T(30)	0.74	0.69	1.12	1.27	1.34	1.01	0.69
	D(50)	0.6	0.63	0.46	0.42	0.4	0.5	0.64
Absorber	EDT	0.59	0.34	0.46	0.49	0.45	0.41	0.34
	T(20)	0.6	0.36	0.48	0.52	0.5	0.44	0.36
	T(30)	0.6	0.37	0.5	0.54	0.52	0.47	0.38
	D(50)	0.7	0.88	0.79	0.77	0.8	0.83	0.88
Absorber	EDT	0.59	0.34	0.46	0.49	0.44	0.4	0.34
+ Diffuser	T(20)	0.59	0.35	0.46	0.49	0.45	0.41	0.35
	T(30)	0.59	0.35	0.47	0.5	0.46	0.42	0.35
	D(50)	0.7	0.87	0.79	0.77	0.8	0.83	0.88

4. PROTOTYPING

There has been much recently written about the rise of robots, however, the reality is robots are already very much here, they are just not very evenly distributed. While robots have revolutionized the way factories build cars and computers, the construction industry has lagged behind other sectors. However, this is now changing and construction robotics is expected to explode in the coming years. Much robotics research in the construction industry has been done on automation and optimization of "dirty, dull, or dangerous" work; however, comparatively little research has been done to discover how robots can extend designers creative potentials. Algorithms can do more than optimization or automation, algorithms can a "trebuchet of creativity," enabling designers to explore new territory never before achieved or imagined. Computation, and its associated advanced robotic digital fabrication, is a way of thinking, and the potentials of this are still not yet understood.

4.1 Robotic Digital Fabrication

In the lab at the Daniels Faculty we operate a robotic CNC milling system consisted of a Kuka KR150 R2700 with KL4000 linear axis with 4500mm travel and a PushCorp 10hp spindle, see Figure 7. The parametric model was used to break the larger surface down into four manageable pieces for installation and fabrication. The surfaces were milled from five layers of MDF. The initial rough stock geometry was parametrically defined, resembling a stepped pyramid. The parametric preparation of the stock geometry was helpful in minimizing material waste during the milling process. From the parametric model, the geometry was exported directly to the robotic milling software, Powermill. The milling software generates the required Kuka robot G-code for three sets of tool paths: a roughing pass, horizontal finishing, and edge-profiling. Three 1:1 prototypes, shown in Figure 8, were constructed to troubleshoot the fabrication process, simulate the final aesthetic, and test installation procedures. For the final pieces, the estimated milling time for roughing pass was four to six hours; finishing was two to three hours and profiling was around 20 to 30 minutes.



Figure 7 Robotic CNC Milling of Sound Scattering Surface



Figure 8 1:1 Partial Prototypes of Sound Scattering Surfaces

4.2 Installation

Once the four pieces of the sound scattering panel were milled, they were primed in workshop with shellac primer. The separate panels were then attached together and mounted to steel studs behind the existing plasterboard walls. The screw holes were filled and the surface and wall were painted with the same wall paint, see Figure 9. 50 mm Claro sound absorbing panels from Decoustics were hung from the ceiling at a distance of approximately 300 mm.



Figure 9 Sound Scattering Wall in Room 341



Figure 10 Detail of Sound Scattering Wall in Room 341

5. MEASUREMENTS

5.1 Background Noise Level

Background noise level (LAeq) was measured at 29.8 dB using a B&K 2250. At the time of the measurement it was very quiet outside the building and in the adjoining hallway. There is a considerable amount of sound transmission into the room from both traffic outside and from people talking and walking by in the hallway outside the room.

5.2 Reverberation Time

Reverberation time is primary measure of room acoustic performance. The reverberation time (T20, T30, and EDT) of the meeting room was measured three times: (1) empty (prior to any intervention), (2) after the installation of the diffuser wall, and (3) after the installation of both sound scattering wall and sound absorbing panels. The measured values are shown in Figure 10. An average of 250Hz-4kHz frequency bands for T20 is 1.102 seconds for the empty condition, 0.986 seconds for the diffuser only, and 0.456 seconds for absorber and diffuser. Due to the complexities of installation, the panel has not yet been removed for testing in the absorber-only condition, though this was simulated (Section 3.4.)





Reverberation time measurements (T20, T30, and EDT)

5.3 Speech Intelligibility

Many of the more accepted room acoustics parameters are now defined in the ISO 3382-1 standard. The work of Haas reintroduced the importance of early arriving reflections to the perceived acoustical qualities of rooms. After this, the work of Thiele explored the perceived effects of combinations of reflections and proposed "Definition" as a measure of definition or clarity (19). "Definition" (D50) is an energy ratio of the energy in the early-arriving reflections (in the first 50 ms after the direct sound) to the total energy in an impulse response. D50 (%) values are considered fair from 0.39 to 0.67, good from 0.67 to 0.86, and excellent from 0.86 to 1.0 (20). The measured D50 values (Figure 11) in both the empty condition, and with diffuser-only were in the "fair" range, while the installation of both diffuser and absorber increased the D50 to the "good/excellent" range.



Figure 12

D50 Values (averaged over 4 positions) comparing the three tests: test 1 – empty room; test 2 – diffuser only; and, test 3 – absorber and diffuser

Speech intelligibility is a critical parameter when considering verbal communication in a meeting room. The Speech Transmission Index (STI) was measured using a B&K 2250 with a B&K ECHO sound source and Dirac Software. A mouth (head and torso) simulator was not used. STI was measured at four positions in the room and with two speaker positions. The source and receiver positions corresponded to seated ear and mouth height for meeting attendees in the room (Figure 1). STI values (Figure 12) are an average of 0.51 in the empty condition, increased to 0.58 with the addition of the diffusing surface, and increased to 0.76 with both absorber and diffuser.





Speech Intelligibility (STI) measurements for four positions for the three tests:

test 1 - empty room; test 2 - diffuser only; and, test 3 - absorber and diffuser

6. CONCLUSIONS

This research project explored a couple of different territories. The project developed a workflow how acoustic performance can be integrated into the architectural design process. In particular, the project explored the design of architectural surfaces and how the form and materiality of these surfaces can impact the acoustic performance of meeting rooms. The project also investigated and tested digital design workflows for that linked architecture computational design processes, with ray-tracing simulation, BEM acoustic simulation, 3D printing, and robotic fabrication.

While the use of FDTD wave visualization has been used successfully on previous projects to explore different surface geometries for sound scattering, the use of commercial BEM software for verifying and quantifying the performance of these surfaces is not something that is common in architectural practice. It was found that for this to be useful in the design process a method of importing user-defined geometries would be necessary – and shouldn't be that hard to implement.

Since 3D printing was first introduced to the architectural profession, the concept of a file-tofactory design process has captivated the imagination of designers. While scaling up 3D printers has proven to be more challenging that initially anticipated, the adoption of processes from industrial robotic manufacturing has proven to be both cost-effective, accessible, and surprisingly customizable. This project borrowed techniques from leading architectural research and applied this to the problem of architectural acoustics. While there were relatively significant new software processes to learn, beyond this the fabrication process worked well and further experimentation should offer even more opportunities for creative expression, both in terms of form but also acoustic performance.

Reflecting on this project and its design, simulation, and fabrication processes, it is clear that there remain many opportunities to customize the fabrication process to integrate acoustic performance into the constructive logic of building construction. The surface as constructed was still essentially a panel attached to an already existing wall, rather than the creation of a new wall, with structure and surface. The panel was a singular material, and there is an opportunity with innovating material processes to bring together multiple materials to create specific architectural or acoustic effects.

While it is recognized that the room acoustic simulation could have been calibrated a little bit more carefully, it should be noted that the simulation predicted a longer reverberation time for both the empty condition and for the diffuser-only condition. The reverberation time measurements for the diffuser and absorber condition closely matched measured results – see Figure 14. Further to this, another observation was that while the measurements illustrated a change in reverberation time and speech intelligibility with the diffuser-only condition – see Figures 12, 13, and 14, the simulations did not capture this difference. The simulation indicated that the condition with the diffuser should perform (almost) identically to the empty room condition.



Figure 14

Comparison of RT Measurements (Solid) with Simulation (Dotted)

This project provides further evidence that the introduction of some sound scattering surfaces can help to improve speech intelligibility, even in absence of absorber. Figure 12 indicates that above the design frequency of 2 kHz there is an increase in D50, and STI values. And while there was some contribution to an increase in acoustic performance in meeting rooms from the sound scattering surface, this project confirms that absorption is the essential component for meeting rooms with good acoustic performance.

ACKNOWLEDGEMENTS

The author would like to acknowledge the National Science and Engineering Research Council of Canada (NSERC) for providing funding for this research through its Discovery Grants program. Decoustics have been a great supporter of this research and donated the sound absorbing ceiling panels. The author would like to thank the John H. Daniels Faculty of Architecture for providing the room, Bohden Tymchuk for assistance with installation, Nicholas Hoban for being such an excellent robot herder, and my research assistants: Jay Yu, Ziju Xian, Alexandra Fiori, Kiefer Savage, Laura Fox, Krystal Kramer, and Ece Ulusoy, for all of the wonderful work.

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