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Volume 31, Number 6, Issue 264 November/December 2022

Full Bandwidth Optimization Software For Critical Listening Rooms

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Abstract

The growing processing power of desktop and distributed cloud cluster computing plays a large role in providing computational architectural acoustic solutions. This presentation will provide a status update on the Non-cuboid Iterative Room Optimization software called NIRO. It offers an iterative approach to full bandwidth optimization of critical listening rooms. The program uses a Finite Element Method (FEM), Image Source Model (ISM), and Non-dominated Sorting Genetic Algorithm (NSGA) to simultaneously optimize the room geometry of any shaped room, including boundary admittances, for any number of listeners and loudspeakers. It minimizes the weighted sum of the modal response and loudspeaker boundary interference response, the spatial uniformity around the mix position, and reflections in the Reflection Free Zone (RFZ). With an optimal room setup, acoustical diffusers and absorbers with a specified resonant frequency, bandwidth, and efficiency are added to the model to optimize the acoustic properties. A combination of FEM, ISM, and an additional geometrical acoustics model is used to generate full bandwidth impulse responses. The RFZ, envelopment, reverberation time, low-frequency response, and temporal decay are optimized and evaluated. Following the addition of HRTFs, stereo auralization is possible. Proof of performance and application examples will be presented.

1.0 Introduction

During the past four decades, I have focused on research that optimizes the design of critical listening rooms and the absorptive and diffusive acoustical treatments needed to achieve this goal. Early attempts using the image model in cuboid rooms to optimize the dimensional ratios were addressed in 1967 with the Room Sizer, and later the Room Optimizer provided optimal locations for the loudspeakers and the listeners. In 2017, following the sale of RPG Diffusor Systems, where I am still Director of Research, I wanted to return to developing software that optimizes critical listening rooms. Together with John Storyk and PK Pandey, we formed a new Research and Education Development Initiative company (REDIAcoustics, LLC). A description of the company and resumes of its talented team are available at www.rediacoustics.com. The first software product was a Non-cuboid Iterative Room Optimizer called NIRO. The program initially used an iterative, wave-based Boundary Element Method (BEM) solution and genetic algorithm to search for the optimal geometry of any shaped room and the positions of loudspeakers and listeners. We designed and optimally located low-frequency absorbers with a specific resonant frequency, bandwidth, and efficiency, which we called Acoustical Parametric EQualizers (APEQs). As research progressed, we evolved to a Finite Element Method (FEM), which allowed shorter run times and the ability to model hanging cloud absorbers. Thus far, the optimization addressed the modal frequency range up to 200 Hz. We then extended the range above 200 Hz by adding a geometric acoustics Image Source Model (ISM) to evaluate low-order specular reflections and a Ray Tracing Model (RTM) to determine the reverberation time.

2.0 Acoustical Distortion

The key goal of this research is to create a neutral critical listening room that minimizes all forms of acoustical distortion, as shown in Figure 1, so that the musical product is transferable to other environments, audiophile listening rooms, and home theatres. When the production environment is neutral and conducive to conversation, comfort, and collaboration, the production engineer can "Listen to the music, not the room." Another slogan we created decades ago states that "If you can't take the room out of the mix, you can't take the mix out of the room." A parallel goal is to design an audiophile listening room and home theatre environment in which the music can be faithfully reproduced by end users, in which they can hear exactly what was created in the control room. We begin by listing the sources and causes of acoustical distortion and how these can be mitigated.

2.1 Modal response

The modal frequency response extends until the individual room modes are no longer spaced and merge into one another. This is referred to as the Schroeder frequency, defined later in the

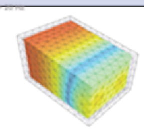
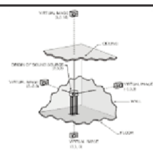
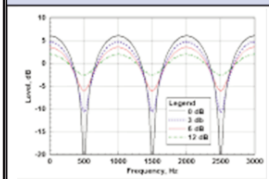
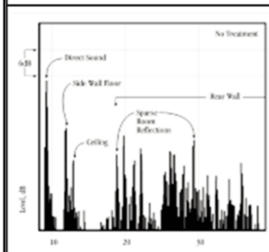
Below 200 Hz			
	Modal Response	1. Geometry 2. Speaker/Listener placement 3. Low frequency absorption	1. BEM, FEM and FDTD wave acousticc optimization 2. Wave acousticc optimization 3. Resonators/Membranes
	Speaker-Boundary Interference response	1. Omnidirectional low frequency interference with adjacent room boundaries	1. Flush/Trihedral mounting 2. Wave acoustic optimization 3. Low frequency absorption
Above 200 Hz			
	Comb Filtering	Coherent interference between a sound and a delayed specular reflection	1. Geometry 2. Absorption
	Poor Diffusion	1. Non-mixing environment 2. Too much absorption 3. Poorly designed diffusive surfaces	1. Optimize geometry 2. Strategic absorption placement 3. Broad bandwidth diffuser design, verified by experimental measurement and/or virtual BEM simulation

Figure 1

paper. The modal frequencies are determined primarily by the geometry, and the degree to which they are heard depends on the location of the loudspeakers, the listeners, and the design and location of low-frequency absorptive treatment.

Another source, which is not as well known, is called the Speaker Boundary Interference Response (SBIR). It is caused by the coherent interference between the omnidirectional frequencies from the loudspeaker and reflections from the boundaries surrounding the loudspeaker. It can be minimized by the placement of the loudspeakers and with the addition of low-frequency

$$f_{n_x n_y n_z} = \frac{c}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \quad \text{Eq. 1}$$

absorption on the room boundaries.

A traditional approach to address modal interference is to use optimal dimensional ratios of Lx, Ly, and Lz to create a uniform distribution of modal frequencies, fnx, ny, nz, based on the solution to the wave equation for cuboid rooms (i.e., rectangular rooms) shown below. Nx, ny and nz are integers, Lx, Ly, and Lz are the lengths in three orthogonal directions for the length, width and height, c is the speed of sound. This approach is a good starting point but involves several assumptions and limitations. For example, it assumes the room is cuboid with 90-degree angles between all room boundaries, that all the room boundaries are perfectly rigid and reflecting with an admittance Y=0, and all room modes are excited and heard. This last assumption can be simulated with loudspeakers and listeners in opposite diagonal corners of the room, although not a very practical situation. To illustrate the limitations of these assumptions, Figure 2, we will now compare a

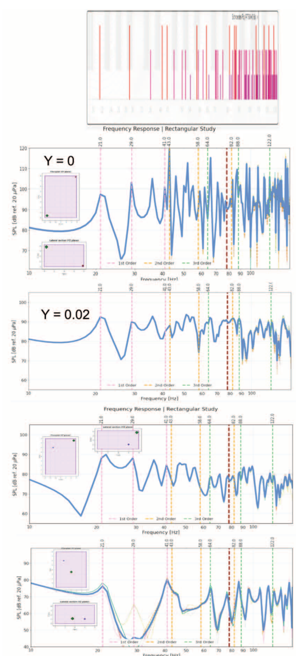


Figure 2

modal frequency prediction using Eq. 1 and a wave-based FEM prediction in the same room with a popular dimensional ratio of 1:1.4:1.9, with loudspeaker and listener in a typical real-world location.

Since this is a cuboid room, the position of the modes in a perfectly rigid room (Y=0) is in good agreement, but the energy levels are not. As we make the boundaries realistically rigid with an admittance of Y=0.02. We see that the response appreciably broadens due to the diaphragmatic nature of typical boundaries. We then move the loudspeaker into a typical position in the room, and the pattern further deviates from the dimensional ratio prediction. Finally, when we move the listener into the typical mid-width location, we observe the dip due to the null of the width mode. The comparison illustrates that optimal room design requires much more than a good dimensional ratio, and we will describe a process.

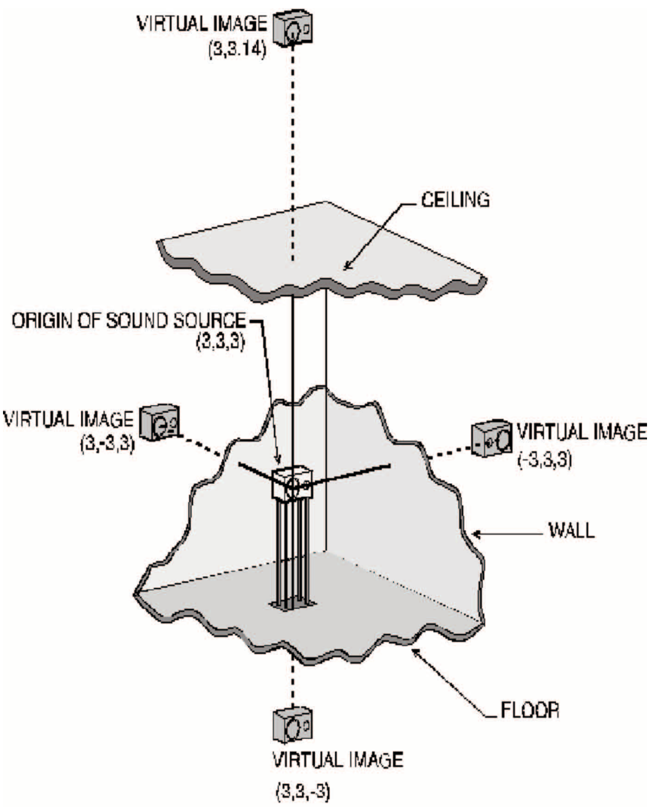


Figure 3

2.2 SBIR

Dimensional ratio predictions also ignore the SBIR, which is important, because if the notch it produces at low frequency is present, it is difficult to remove. We hear the coherent sum of the real and all virtual sources in the room, Figure 3. This potential problem can be minimized by optimally locating the loudspeakers or treating the surfaces surrounding the loudspeaker with efficient low-frequency absorption. In Figure 4, we illustrate the potential problem the SBIR introduces. In Figure 4, we see that the notch increases in depth as the number of boundaries is increased from 1 to 3. Another potentially helpful issue is that as the loudspeaker moves closer to the boundaries, the notch moves to a higher frequency where it is more easily treated with porous absorption. For

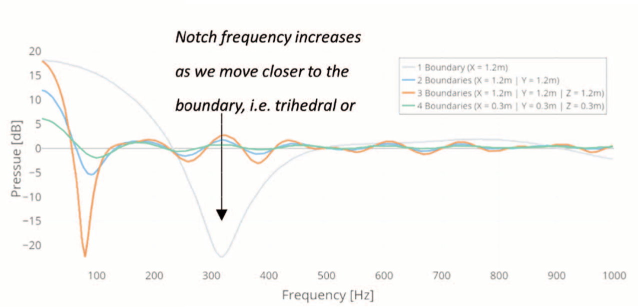


Figure 4

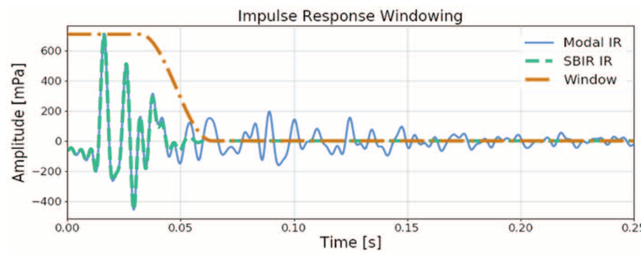


Figure 5

this reason, we suggested in the RFZ control room design in 1996 that the loudspeakers be flush mounted. We can estimate the SBIR in the NIRO program, which we will describe later, by windowing the early part of the room's impulse response, as seen in Figure 5.

2.3 Specular Reflection Comb Filtering

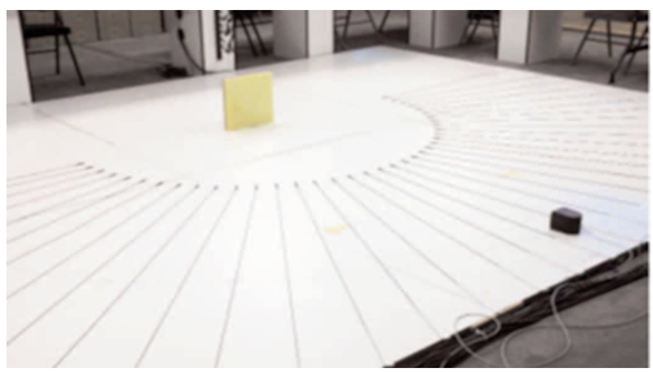


Figure 6

Specular reflections are similar to optical mirror reflections, in which the angle of reflection is equal to the angle of incidence. However, what are the conditions for a specular reflection, or put another way, what is the onset frequency for a specular reflection? The answer can be found by measuring the polar response from a

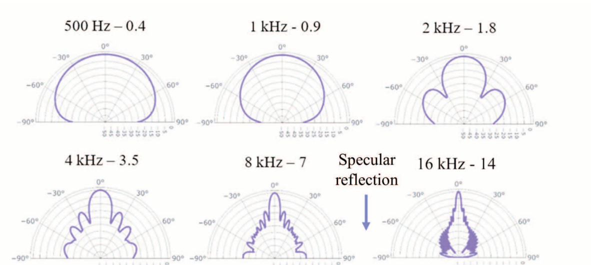


Figure 7

flat panel at various wavelengths in a goniometer, shown in Figure 6. The polar responses are shown in Figure 7 for 6-octave band center frequencies from 500 Hz to 16 kHz. Above each polar response, we show the frequency and the ratio of the panel width divided by the wavelength, e.g., 1 kHz – 0.9. When the panel width and the wavelength are comparable, the scattering is uniformly diffuse. However, when the ratio reaches approximately 10, we see the scattered energy being focused in the specular direction. This means that different size surfaces will scatter specularly at different frequencies. The onset frequencies for a 3-, 5- and 9-foot panel are 3,000 Hz, 1,800 Hz, and 1.000 Hz, respectively. When the direct sound is combined with a delayed reflection, the audible consequence is a distortion called comb filtering, because the nulls are evenly spaced on a linear frequency axis like the teeth on a comb. This interference is shown in Figure 8, where the notches' depth increases as the reflection level reaches the level of the direct sound.

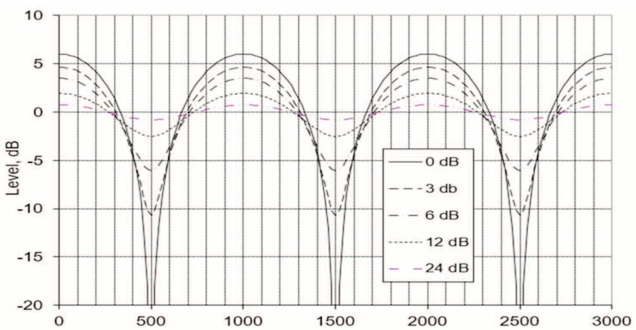


Figure 8

2.4 Poor Diffusion

While classical architecture contained many types of diffusive elements incorporated to the rooms, like statuary, columns, coffered ceilings, and balustrades, their performance was not quantifiable. In addition, today's architecture is missing these scattering

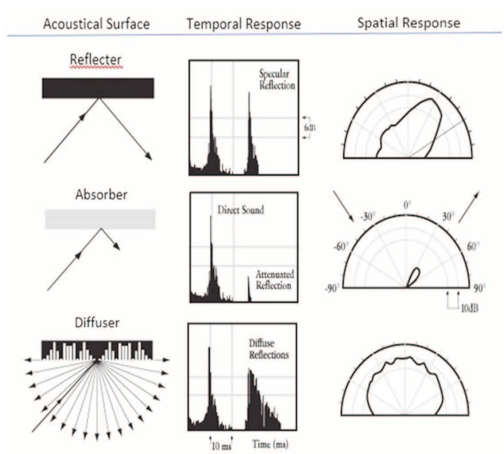


Figure 9

surfaces. Following the introduction of quantifiable reflection phase gratings by RPG Diffusor Systems in 1983, diffusers have continued to evolve and are now used as a complement to absorbing surfaces. At this time, there is a full complement of diffusing surface topologies to be included in contemporary architecture (www.rpgacoustics.com). While absorbing surfaces attenuate

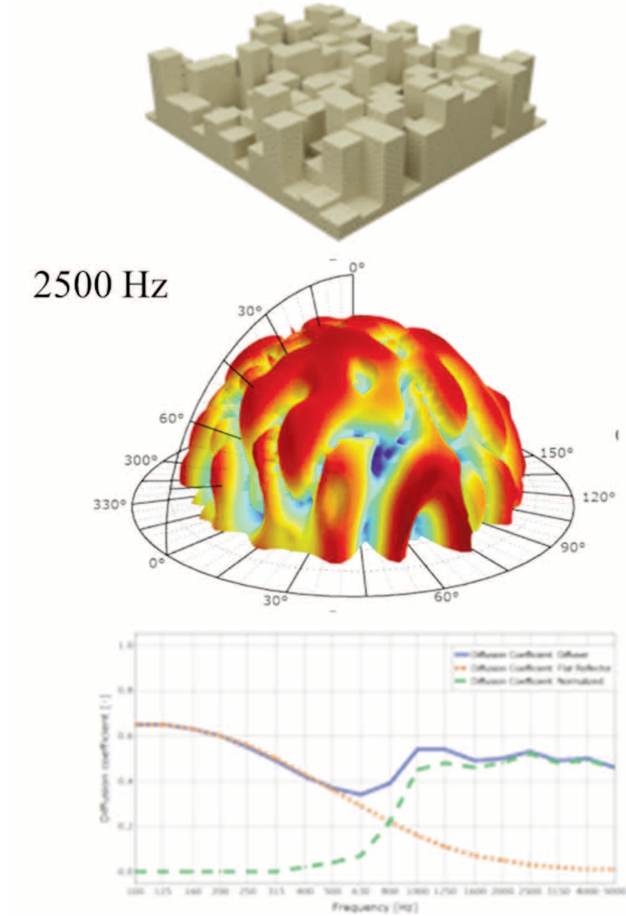


Figure 10

specular reflections, diffusing surfaces control them by uniformly distributing them both temporally and spatially, as seen in Figure 9. Today, the literature contains both absorption and diffusion coefficients, which are obtained from experimental goniometer testing. A recent wave acoustic virtual goniometer BEM program called VIRGO (POMA article available) allows the evaluation of the 3D polar responses and diffusion coefficient of any shaped surface, according to ISO 17497-2, from a 3D CAD file, simplifying the evaluation of new topologies without the need for experimental scale model testing. In Figure 10, we show the simulated 3D polar response and normalized diffusion coefficient for RPG's Skyline diffuser.

3. NIRO software

In order to optimize room design over the complete audio spectrum, we need to utilize the wave acoustic FEM below the Schroeder frequency, fs, in which T is the reverberation time and V is the room volume, Figure 11, and above fs , the geometrical acoustics ISM and the RTM, Figure 12. Geometrical acoustic models essentially follow rays through their reflection history, FEM requires a mesh of the room boundary, as well as the internal volume, as shown in Figure 13. The approach used by the NIRO program to optimize the room is shown in Figure 14. It involves three sections, Room Geometry, Source and Receiver positions which are determined via an iterative multi-objective search algorithm,

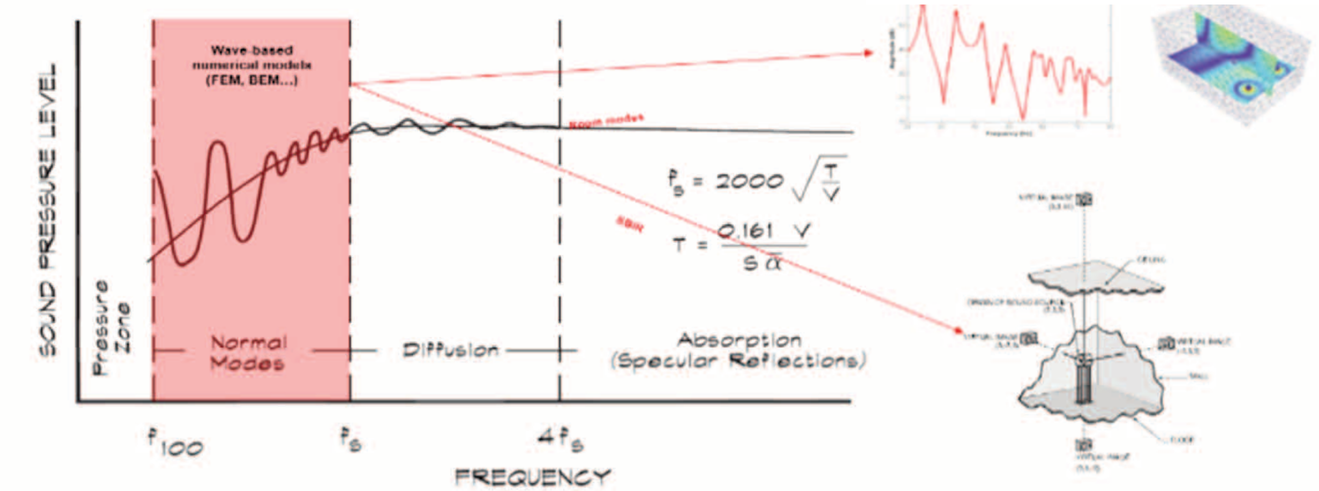


Figure 11

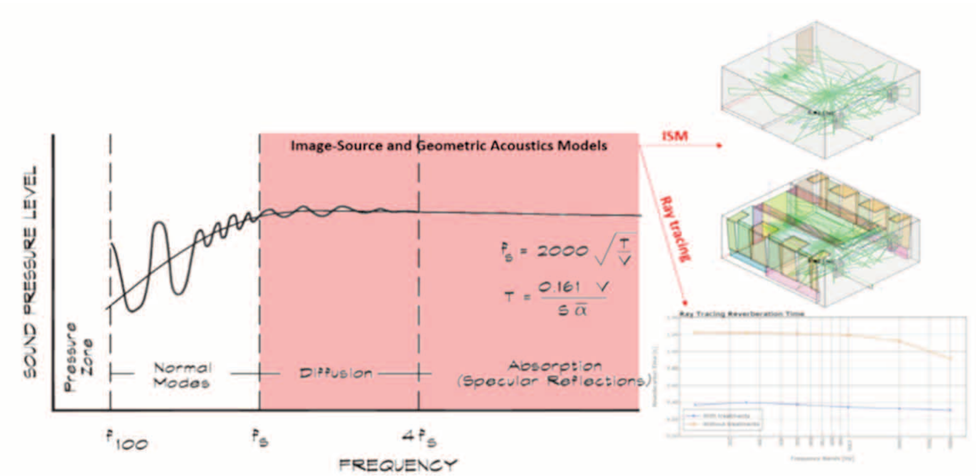


Figure 12

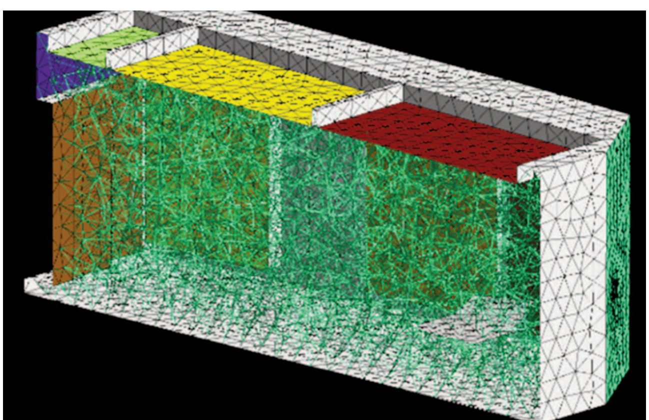


Figure 13

the Acoustical Treatment (Acoustic Parametric Equalization) process, and finally the Auralization section.

3.1 The Challenge

In Figure 15, we show two views of the pressure distribution in a room at various frequencies up to 200 Hz. For example, at 61 Hz the contour plot shows pressures ranging from high-pressure emphasis to low-pressure nulls. The situation is made even more complicated since the pressure contour changes for each frequency. The challenge is to iteratively navigate through this changing pressure minefield to find the “sweet spot” for a given geometry and the locations for loudspeakers and listeners where the pressure variation is acceptable.

3.2 How Does NIRO Optimize All Metrics

- Utilizes complex surface admittances to characterize the room’s boundaries and acoustical treatments
- Simultaneously, optimizes the location of woofers and loudspeakers (whether freestanding or soffit mounted), listeners and the room’s vertices for any shape room
- Uses a wave-based FEM to evaluate the low-frequency range
- Uses the ISM and RTM to evaluate the reflection free zone, RFZ, and the diffuse field zone, DFZ, and the reverberation time
- Combines the methods above into a multi-objective optimization to find the best solution within the architectural constraints
- Applies broad bandwidth diffusers and absorbers with specific center frequency, peak absorption, and bandwidth, APEQs, to damp temporal modal ringing.

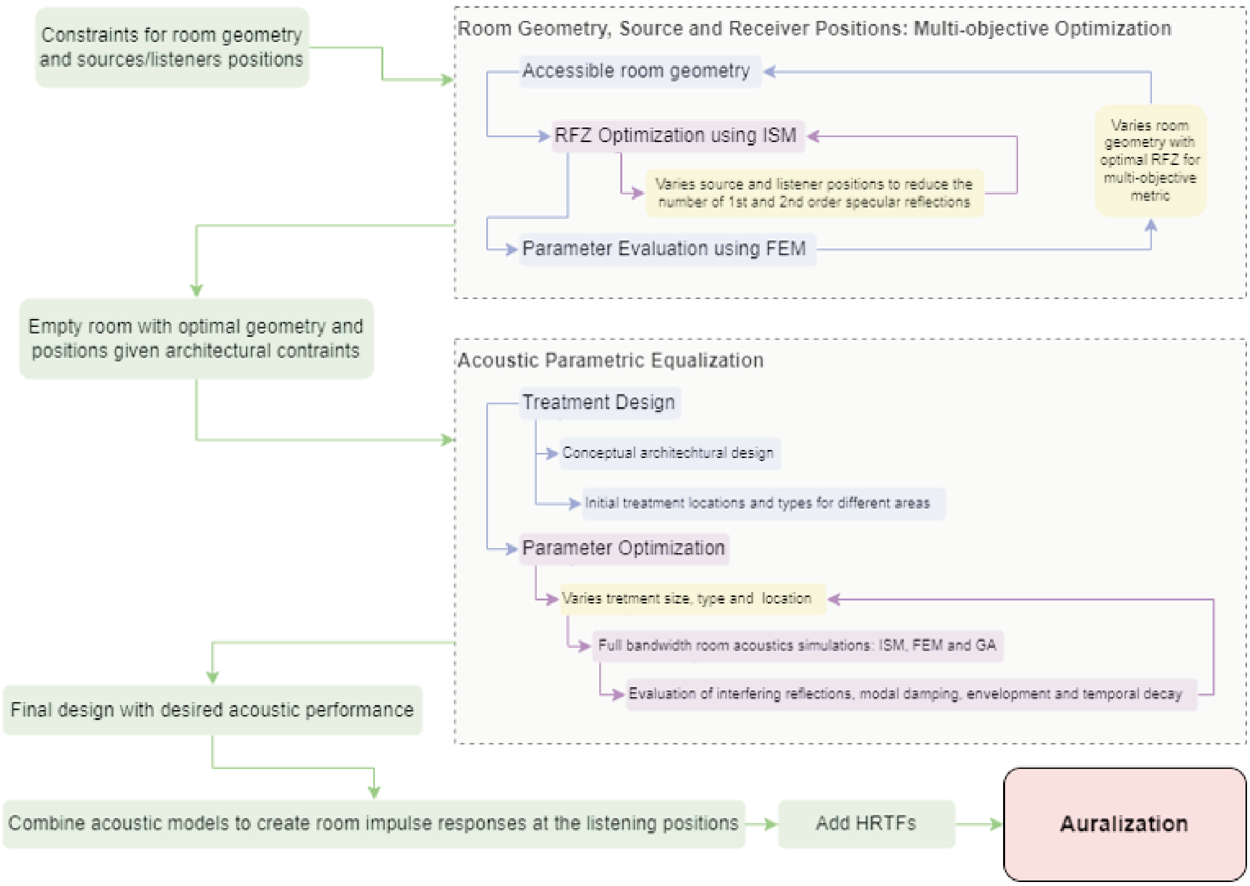


Figure 14

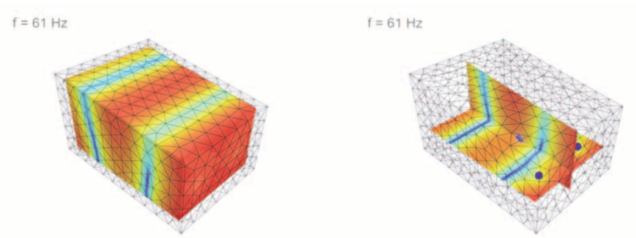


Figure 15

3.3 Optimizing The Geometry, The RFZ And The Positions For The Loudspeakers And Listeners

In this step, Figure 16, we use an iterative, multi-objective genetic algorithm (NSGA-II) to optimize the weighted modal response and SBIR, the spatial average surrounding the listening positions with an FEM and an ISM to minimize the 1st and 2nd order reflections in the reflection free zone, RFZ, which is the time between the direct sound and the first arriving reflections from the rear wall.

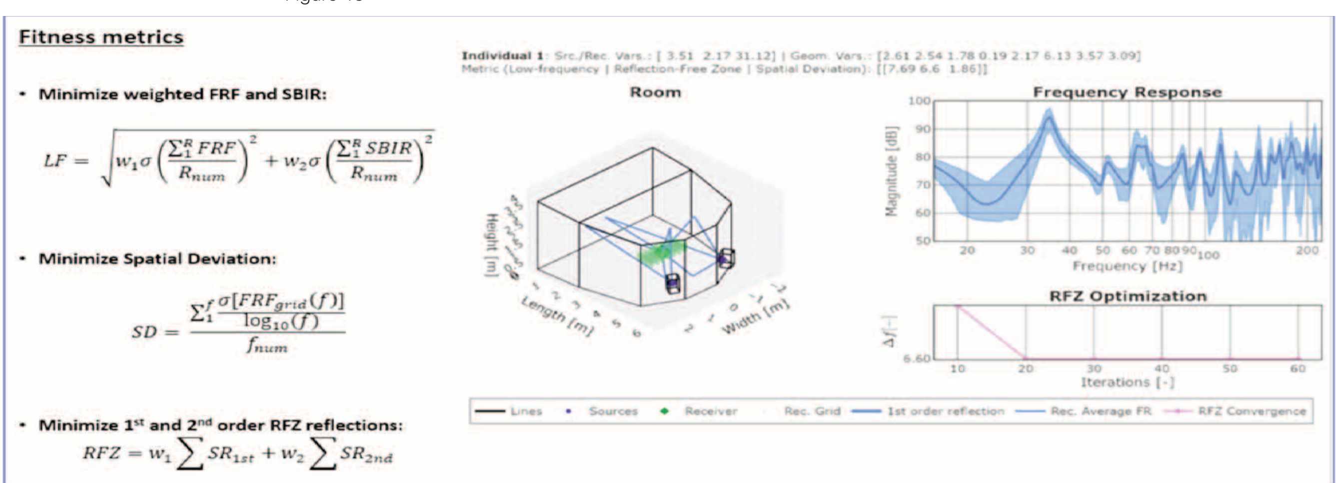


Figure 16

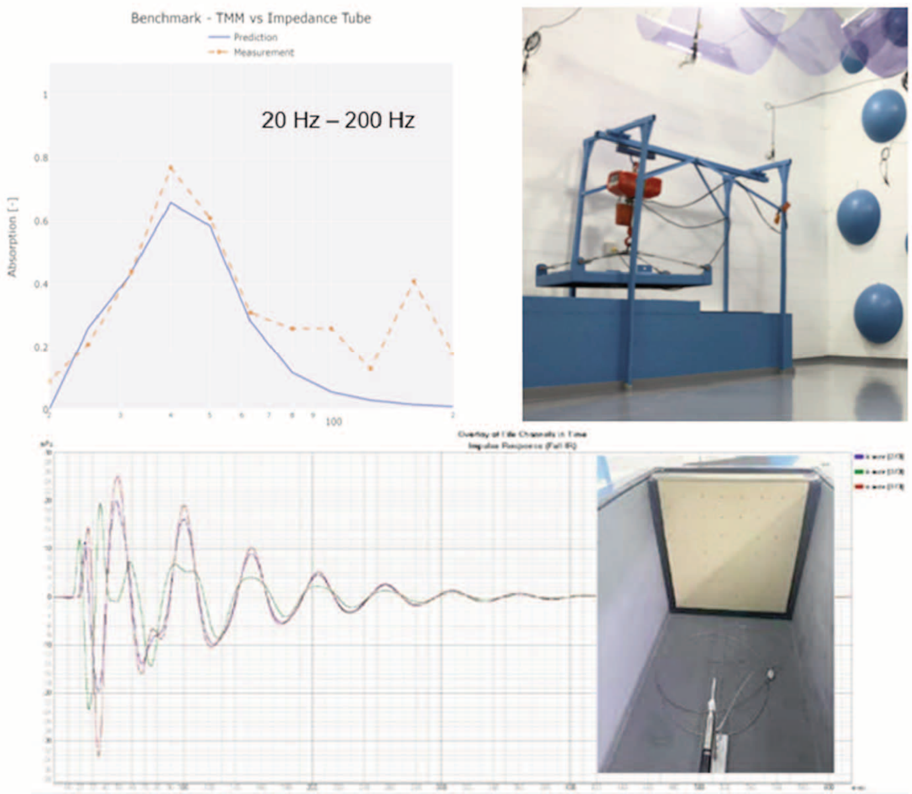


Figure 17

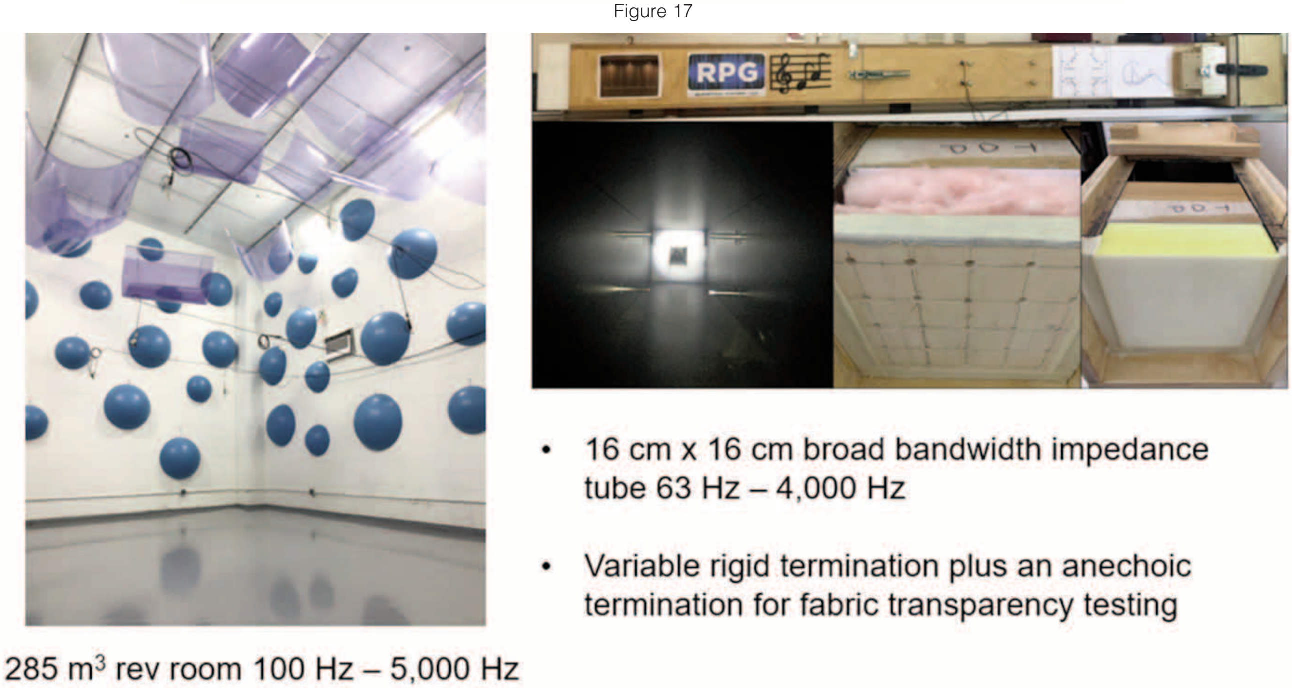


Figure 18

Three fitness metrics are minimized. The goal of the first metric, LF, is to minimize the standard deviation of the weighted sum of the modal frequency response, FRF, and the SBIR. The second metric, SD, aims to minimize the average spatial standard deviation of the frequency response (FRF) over a 3D grid of listening positions. Lastly, the third metric, RFZ, aims to minimize the number of 1st and 2nd order specular reflections in the RFZ, to minimize comb filtering interference caused by early reflections. On the right side of the graphic, we illustrate the room geometry, with first-order specular reflections between the loudspeakers, the rear, side walls and ceiling, and the listening grid. Also, we show the average frequency response (solid line), spatial variation (light blue area), and the number of reflections in the RFZ. This is a static view of one step in an iterative animation, which can include hundreds of iterations. Once we have found an acceptable geometry, RFZ, loudspeaker, and listening locations, we design and locate low-frequency absorbers with a specific resonant frequency, bandwidth, and efficiency to further optimize the design metrics within the architectural constraints. We combine the wave and geometric acoustic results and evaluate various options until we achieve an acceptable broad bandwidth design. We then add Head Related Transfer Functions (HRTFs) to allow us to auralize the final impulse response.

4. Acoustical Treatment Prediction And Experimental Measurement

In the FEM, boundaries and acoustical treatment must be characterized by the complex impedance or its reciprocal, the admittance. Therefore, to accurately characterize the low-frequency acoustical treatments, they are predicted with a Transfer MatrixMethod (TMM) and experimentally measured in RPG's 25-foot long, 10-ton impedance tube. The tube is 2 feet x 2 feet allowing characterization of typical panel size treatments from 20 Hz - 200 Hz. In Figure 17 left top we show the agreement between TMM and the measurement. In Figure 17 right top, we show the impedance tube with the lid open in RPG's new Acoustical Research Center (ARC) 285 m3 reverberation chamber. In Figure 17 left bottom we show the three impulse responses at the different sample to microphone distances needed to calculate the transfer function and normal absorption coefficient. Figure 17 right bottom shows a Helmholtz resonator in the tube. To determine acoustical characteristics, we can make use of RPG's reverberation chamber, Figure 18 left, and the 16 cm x 16 cm broad bandwidth impedance tube, Figure 18 right. The tube has the ability to use a rigid termination or anechoic termination, which we use to determine fabric transparency. This tube uses four microphones located at a quarter of the width and height, in three positions, to cancel the first lateral and vertical modes extending the upper frequency from 1,000 Hz to 4,000 Hz. In the photo, we can see the four microphones looking toward the loudspeaker, a Helmholtz absorber sample, and a porous absorption sample.

5. Final optimized results

The following graphs illustrate the final results. Figure 19 shows

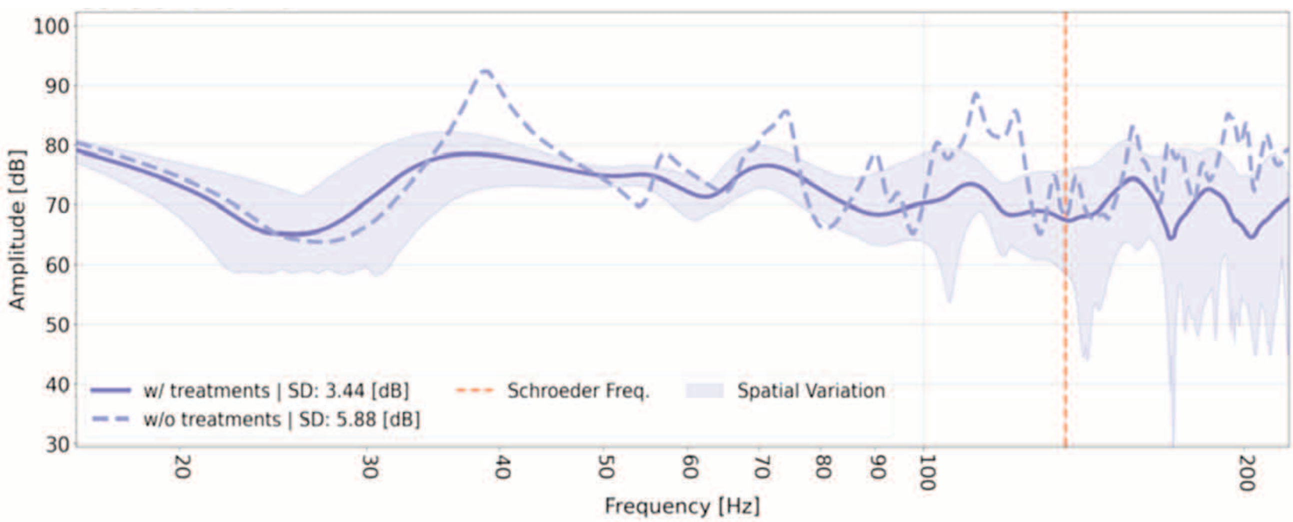


Figure 19

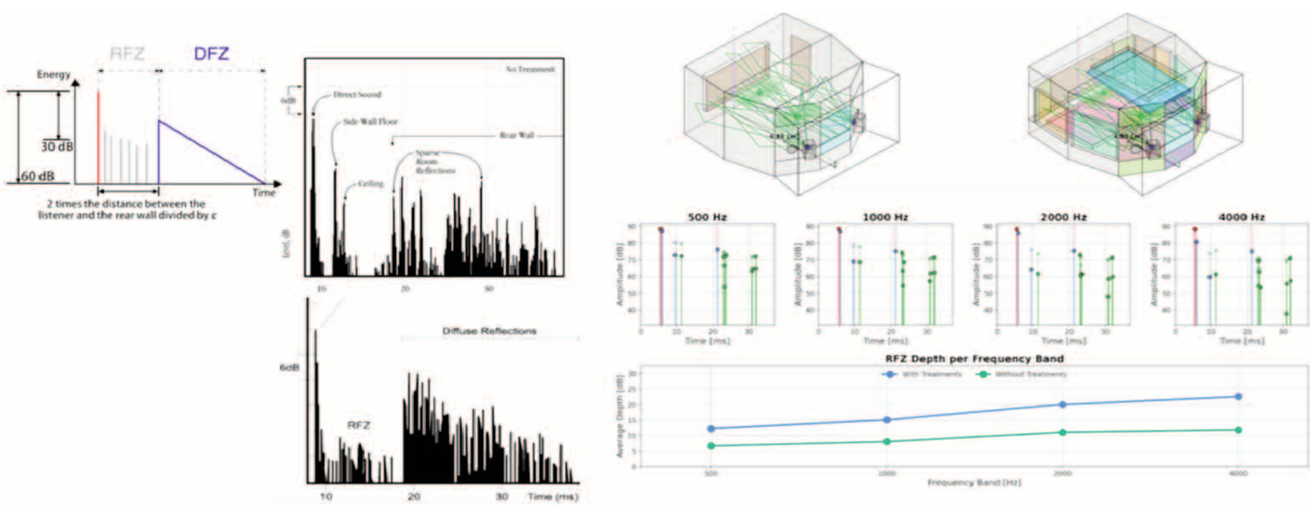


Figure 20

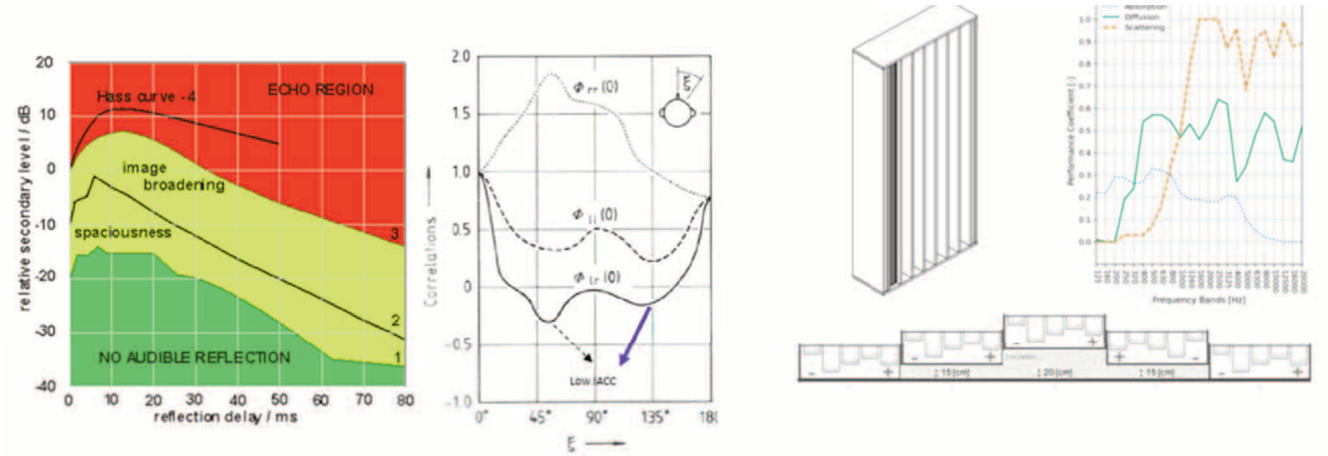


Figure 21

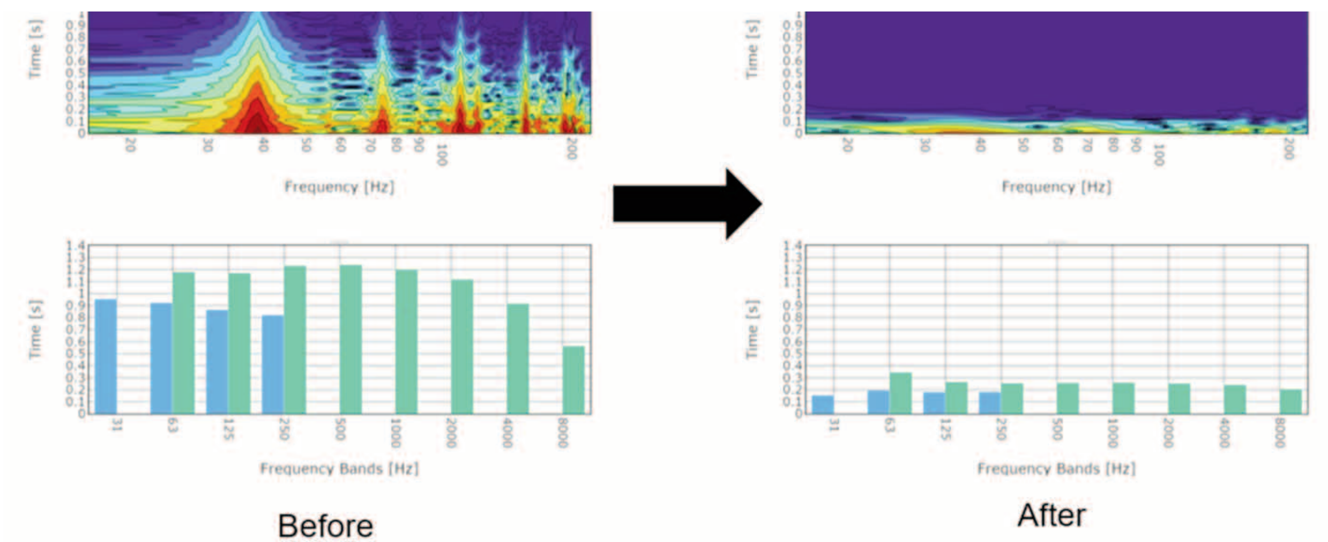


Figure 22

the final low-frequency response up to 200 Hz, without and with acoustical treatment, and the spatial variation is shown. In Figure 20, we define the RFZ and DFZ and illustrate the design goal of minimizing reflections in the RFZ and introducing a temporally dense set of linearly decaying reflections in the DFZ. The levels of the RFZ reflections before and after geometry determination and applied absorption are shown, as well as the bandwidth of the RFZ with level reduction before and after treatment. Decades of psychoacoustic research by Michael Barron and Floyd Toole have correlated the level of reflections with respect to the direct sound and their time delay with various subjective sensations, Figure 21 left. Yoici Ando determined the optimal lateral arrival angles for reflections which create a minimum in a parameter called the Inter-Aural Cross Correlation (IACC), Figure 21 middle. Since we are controlling the frontal reflections in the RFZ, we utilize the second dip in the IACC (blue arrow) to provide envelopment. These lateral reflections arrive from the rear wall diffuse reflections, bouncing to the listening positions from the rear side walls. We have used this psychoacoustic research to design and locate broad bandwidth, modulated, and optimized, third-generation fractal diffusers (Modffractals) on the room's rear wall to provide a sense of ambiance and envelopment, Figure 21 right. Finally, in Figure 22 left top and left bottom, we show the temporal decay and reverberation time before treatment, respectively. In Figure 22 right top and right bottom, we show the final results after treatment. The goal is2to arrive at a temporal density that decays uniformly over the

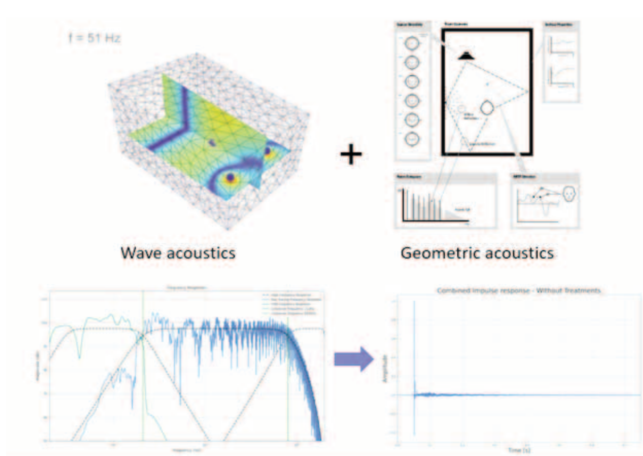


Figure 23

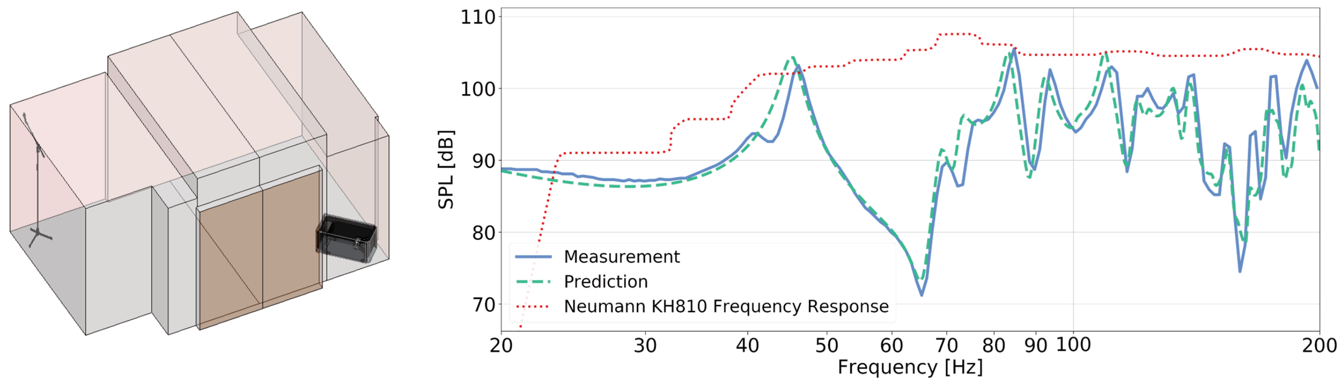


Figure 24

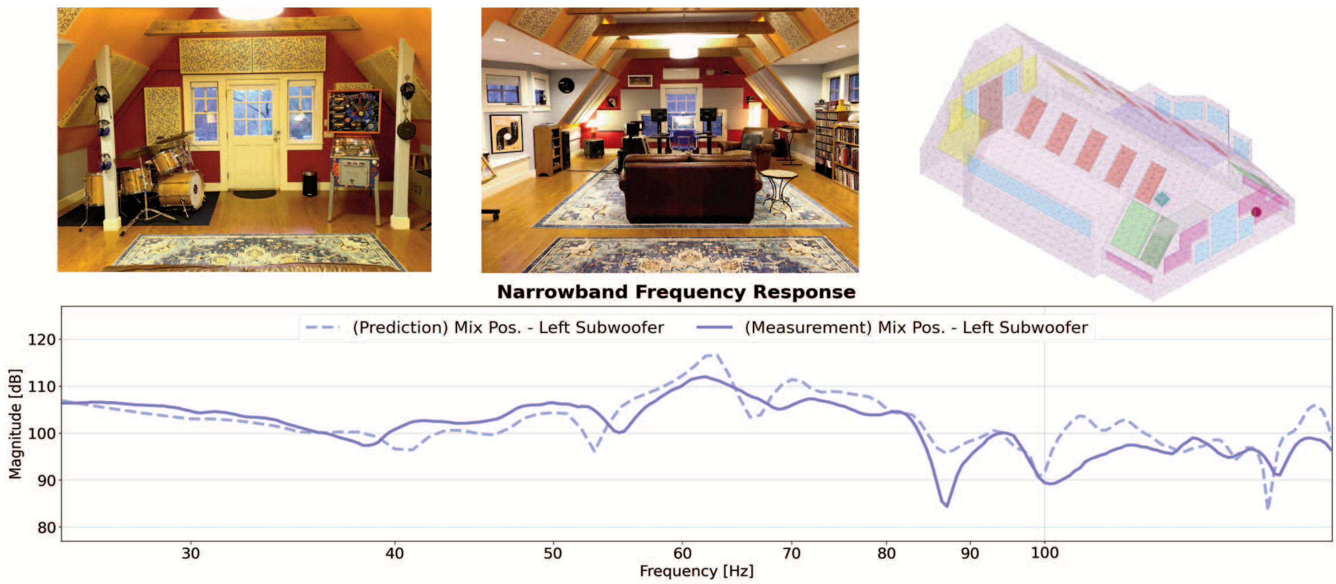


Figure 25

modal frequencies for a tight low end and a uniform reverberation time over the full bandwidth.

6 Auralization

In order to auralize the room, we must combine the results from the FEM wave-based optimization and the ISM/RTM geometric analysis to form a broad bandwidth impulse response. Figure 23 illustrates how the frequency responses are combined, and transformed to yield the full frequency impulse response.

7. Proof of concept

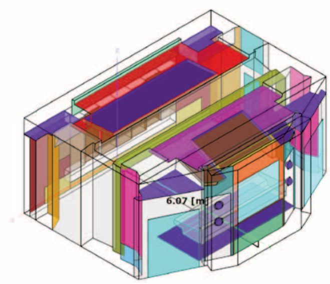
To verify the accuracy of an early BEM modal prediction up to 200 Hz, we stiffened the boundaries of an existing storage room. Placed a subwoofer in the lower right corner and the microphone in the opposite diagonal corner to excite and record all modes. The comparison is shown in Figure 24. While we couldn't characterize every surface in the room, the good agreement was gratifying and encouraging to continue to evolve the software.

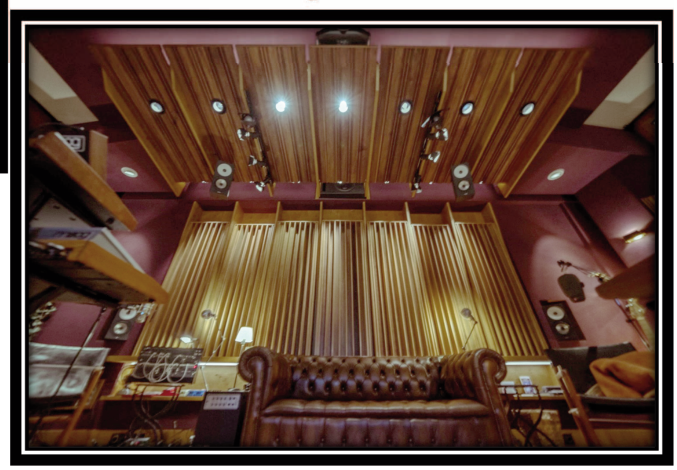
8. Projects

To date we have optimized roughly 70 projects worldwide, with more being completed for which we have in situ measurement comparisons. The following are examples of an optimized residential recording studio, a professional recording studio, and a residential home cinema.

8.1 Abbott Road

When the pandemic occurred, the dean of Berkeley College of Music, Rob Jaczko no longer had access to the facilities at the school and decided to update and optimize an attic studio he had in his home. This was an existing complex room to mesh, as you can see in Figure 25. Acoustical treatment was designed, located, and installed on existing room boundaries, and the comparison between the predicted and measured modal response is shown. While not all the room's contents could be modeled, the agreement and client's approval were encouraging. Project execution and architectural coordination for this unique geometry was developed by the REDI team and WSDG. Photo by Rob Jaczko.





8.2 Mix With The Masters @ Rue Boyer

Figure 26

This next project is an internationally renowned educational recording studio in Paris. Successful engineers/producers share their expertise on successful commercial records with enrolled classes of students. Prior to their studio, Rue Boyer, these classes were held in other studio locations. In Figure 26, we show a wide angle and rear wall view of the studio, along with a model output of the NIRO program, illustrating the type and placement of acoustical material. Because this control room is used for mixing/production and educational classes, the console is mounted on a lift mechanism and can be lifted into and below the room. This offered an opportunity to perforate the platform the console is mounted on and used as a broad bandwidth low-frequency absorber. A photo of this is shown in Figure 27. Project execution and architectural coordination for this unique geometry was developed by the REDI team and WSDG. Photo courtesy Mix with the Masters.

Figure 27

8.3 Harmonia Residence Home Cinema

This project is a residential home cinema. The floor plan, front and rear sections are shown in Figure 28 with acoustical treatment in place. A low-frequency absorber is added to the front wall behind the screen, the risers are perforated Helmholtz resonators, the ceiling is treated with a combination of broad bandwidth porous absorption and resonators, and specular reflections coming from the side walls are treated with porous absorption. In Figure 29 we show a photo of the completed room. Technical interior design by WSDG. Photo courtesy of Maxicon.

9. Conclusion

The goal of this paper is to describe the potential sources of acoustical distortion in critical listening rooms and how these can be mitigated. We described a new full-frequency software program combining wave and geometrical acoustics to simultaneously optimize the geometry of any shaped room, the locations of any number of freestanding or soffit-mounted loudspeakers and subwoofers, and the location of listeners. The program also designs, tests, and locates acoustical treatment to optimize the full frequency response, temporal decay, and reverberation time. The full-frequency impulse response can also be used to auralize the room. NIRO is an optimization service offered to acousticians, architects, recording studio and home theatre designers, system integrators, and end users. Following consultation and optimization, the deliverable is a detailed report with illustrated optimization solutions. The software has been verified in numerous projects. Further NIRO information can be found on LinkedIn at https://www.linkedin.com/company/rediacoustics. Further technical and educational information can be found in my weekly LinkedIn posts at #drpeterdantonio and in my book with Professor Trevor Cox, *Acoustical Absorbers and Diffusers: Theory, Design and Application*, 3rd Edition, CRC Press 2017. **WSR**

In discussions with Dr. D'Antonio, he added the following comment to put the article in context.

Clearly this is a very technical article that will resonate with readers on different levels, based on their background, type of project and degree of desired optimization. The article is meant to describe what is now possible to achieve in professional recording studios and dedicated home cinemas and open a dialog for further discussion. In addition to optimizing all of the variables namely, interfering reflections, frequency response, temporal decay, and reverberation time, it can also address more limited solutions that depend on the limitations of the type of project. We could consider the following three scenarios:

The room shape and décor of the room are fixed, and the goal is to only optimize the locations of free-standing or flush mounted speakers (including multiple subs) and listening positions within accessible areas

The room shape is fixed, but in addition to optimizing speaker and listener locations, additional acoustical treatment can be added in certain locations and in keeping with a desired aesthetic

The project is a new room and the shape, the locations of speakers and listeners and acoustical treatment can be optimized within given architectural and aesthetic constraints.

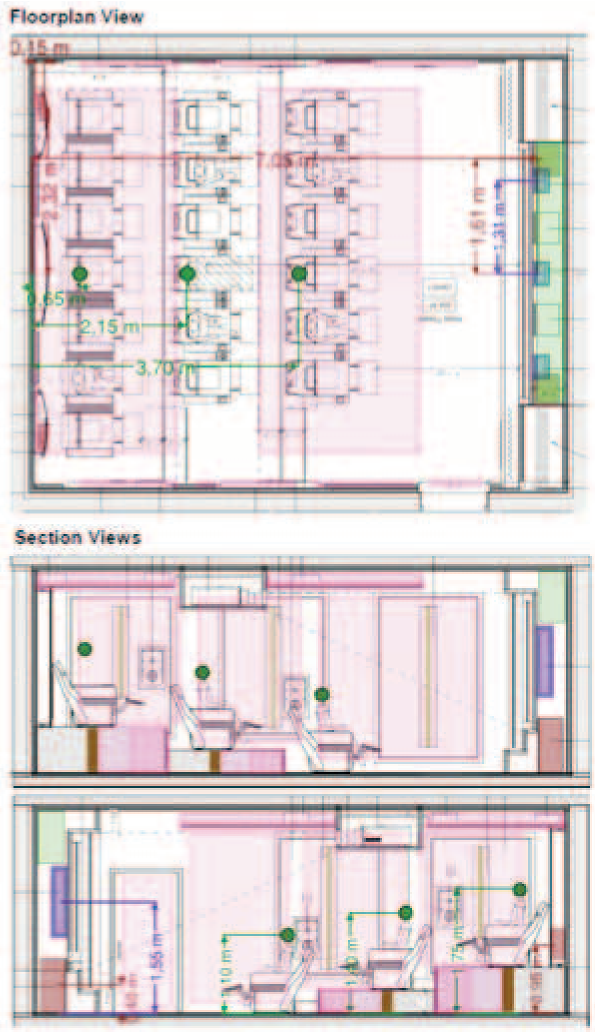


Figure 28


Figure 29