WSR's Holosonic™ Home Theatre System
Part III — Acoustical Design Part I

GARY REBER

Widescreen Review's New State-Of-The-Art Reference Theatre At New Facility

This is Part III of a series of articles on the design, development and execution of the new state-of-the-art Reference Home Theatre Laboratory at *WSR's* new office facility in Temecula, California (north of San Diego, southeast of Los Angeles) that serves as *Widescreen Review's* and Surround Music's review laboratory. Part I appeared in Issue 48. The conclusion of the series, Part VII, will appear in Issue 53 (October 2001).

Our dedicated theatre measures 26-feet deep x 21-feet, 8.6-inch wide x 13 feet, 11.9-inch high, or approximately 8,000 cubic feet in volume.

The entire home theatre room and the rear-projection room were constructed with the complete QuietZone® Noise Control System build-materials package from the Owens Corning Science and Technology Center Acoustical Design Division. In this Part III, Dr. Peter D'Antonio, President of RPG Diffusor Systems, Inc., presents an article about the acoustical design approach taken for the theatre. RPG's VariScreen and Skyline acoustic treatments dominate the theatre's design. By using RPG's VariScreens we are able to have variable acoustic control to adjust for various loudspeaker systems under review.

As a follow-up to Part II in Issue 49, I visited with Ken DeLasho of the Industrial Acoustics Company during a recent business trip to New York City. By implementing an integrated system of QuietZone build materials and IAC acoustic doors, we were able to achieve a Sound Transmission Class rating of STC-63 for the theatre construction and a STC-61 rating for the doors. STC is a single number (laboratory) rating of how well a structure (wall, floor, door, window partition) reduces sound passing through it. A minimum STC-60 (partition) performance level is recommended for home theatre.

Mr. DeLasho showed me a new series of acoustic doors which are wrapped in a wood veneer finish to complement home interiors. The doors looked extremely attractive with performance at the highest STC values. IAC doors are the best acoustic doors made and the subject of conversation by everyone who experiences our new home theatre laboratory. These doors work —shutting out noise potentially entering the theatre and sounds in the theatre from leaking into the other areas in our new facility.

The following is a collage of pictures taken of the IAC doors and RPG installation. The pictures were taken by either myself or Dave Kessler, proprietor of the David Kessler Studio. ■

Acknowledgements

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Wood Veneer Wrapped IAC Door

Workers Fitting IAC Door Frame In Place

IAC Consultant Henry Osgood With Door

Minimizing Acoustic Distortion In Home Theatres

Acoustics For WSR's Holosonic™ Home Theatre Part I

DR. PETER D'ANTONIO

Professional Acoustic Technology For Home Theatre

It has been interesting to witness the evolution from monophonic recordings to today's discrete digital surround formats. Sonically, these electronic advances have made great strides towards more realistic reproduction. Despite the marvelous electronic advances in digital hardware, sound must eventually travel the acoustic analog path from loudspeaker to our ears. At RPG® Diffusor Systems, Inc. we have been developing digital acoustical technology to keep pace with these electronic advances. When *Widescreen Review* was considering moving to a new location, Publisher and Editor-In-Chief Gary Reber asked if RPG would be interested in collaborating in the design of a new state-of-the-art listening and viewing laboratory. I agreed for three reasons:

1. RPG's mission has always been continuous acoustical innovation through a commitment to basic acoustics research and the new listening/viewing laboratory would offer an opportunity for research.
2. I was attracted by *WSR's* desire to use the laboratory for education and seminars and agreed to participate as an instructor.
3. *WSR* offered an opportunity to publish a scientific explanation of the causes of acoustic distortion that rooms may introduce and the solutions to minimize these potential problems.

In this article I would like to describe what was done to create the *WSR* laboratory, but more importantly give readers a fundamental understanding of acoustical distortion so that they may use the available solutions to address any critical listening room.

As President, I would like to introduce RPG to you, because I think it is important to consider the source of what you read. Since founding RPG in 1983, we have strived to continually expand the acoustical palette with an ever-increasing number of acoustical products based on a wide range of technology including mathematical number theory, fractals, spread spectrum modulation, boundary element and multi-dimensional optimization techniques, etc.

RPG is proud of the fact that the industry's leading acoustical consultants and studio designers have specified RPG products in over a thousand forefront music facilities around the world for 17 years. At this time, there are tens of thousands of our acoustical systems installed and in use by satisfied industry professionals. Our clients include artist studios for Peter Gabriel, Reba McEntire and Whitney Houston; leading professional studios like Sony Music & The Hit Factory; mastering facilities like Gateway Mastering & Sterling Sound; concert halls like Carnegie Hall and Frits-Philips Muziekcentrum; broadcast facilities like CBS, HBO & NBC and record companies like Sony, Mercury, Polygram, Telarc and DMP. In short, the industry's leading facilities. When you enjoy your next CD, DVD, movie, video, radio broadcast, or live symphonic performance, chances are you are hearing RPG technology in operation, because RPG products are now used in every facet of the recording process and have become the acoustical standard of the music industry. We strive to maintain this position of leadership and are excited about bringing our professional acoustic technology to the home theatre market.

As Chairman of the AES Working Group on the Characterization of Acoustical Materials, we have also developed new measurement methodology and proof-of-performance metrics to help designers and end users evaluate potential acoustical products. The Audio Engineering Society (AES) recently published an information document entitled AES-4id-2001 describing a procedure to evaluate how uniformly a surface scatters sound. This test in conjunction with the standard random incidence absorption coefficient (ASTM C423) allows acousticians and end users to evaluate potential acoustical surfaces. We urge you to request official test data from manufacturers of all acoustical products measured according to acoustical standards or information documents. In this way, you are making educated purchases and support the scientific advancement of our industry.

We have designed a Web site (www.rpginc.com) that is hopefully educational as well as informative. We invite you to visit to obtain further information that this article might not have an opportunity to present. We invite your comments on how you perceived the site and also welcome comments on how it might be improved.

Widescreen Review's Listening/Viewing Laboratory

WSR presented us with the following acoustical requirements:

1. Determine the optimum room dimensions within minimum and maximum distance limits for the length, width and height.
2. Optimally position 7 matched left/center/right front, left/center/right rear, and a ceiling loudspeakers and additional subwoofers. Since the main speakers contained two woofers per speaker, this amounted to 14 low frequency drivers, in addition to the subwoofers.
3. Optimally position the listener to be equidistant from all speakers and be located at the center of a hemisphere with a radius of 10 feet, the optimal listening distance determined by the loudspeaker manufacturer. The left/right front and left/right rear loudspeakers were requested to be constrained to the corners of an inscribed square with a dimension of roughly 14 feet.
4. Provide a room that was acoustically flexible to address the current listening/viewing requirements, plus any future hardware or audition formats.
5. Provide a room that was acoustically compatible with multichannel music, movies, education, and basically comfortable to be in and not overdamped.

Before we address the *WSR* requirements, I would like to discuss the potential forms of acoustical distortion that a room can cause. This will hopefully provide an understanding of how to address any room.

Because of the wide scope of this discussion, *WSR* has graciously allowed me to present the material in this comprehensive article,.addressing the causes of Acoustic Distortion, and then how we minimize Acoustic Distortion, with particular emphasis on the *WSR* laboratory.

Why are Home Theatre Acoustics Important? The simple answer is because the acoustics of the room are audible. Loudspeaker performance is directly linked to the home theatre's acoustics, because the speaker and the room are one. The reason is that the frequency response, imaging and spatial sensation we perceive, depend on a combination of the direct sound from the loudspeaker and the indirect reflected sound from the room's surfaces. Our ear/brain (auditory system) hearing mechanism processes both the direct and reflected information to determine all of the psychoacoustical emotions and sensations we derive from sound.

Today, the music industry is experiencing exciting new discrete digital playback surround formats, consisting of left/center/right front speakers and additional discrete surround speakers. In addition, an effects channel is also provided that is generally used with one or more subwoofers. For movies, the center channel is usually devoted to dialogue. For music only CDs, the producer has a new audio palette, which he can use to create new and exciting sound designs and perspectives. We can now listen to music as an observer or as part of the band. We no longer rely on a stereo phantom center channel, with panned stereo information. We now have a "real" center channel and panned information from center to the left/right channels. The left/center/right speakers can be monopole, bipole or dipole. Since this new format is so powerful, it is not surprising that at the moment there are two possible surround speaker formats—dipole vs. monopole/bipole. The dipole surrounds are typically located slightly above ear level to the sides of the listening position. The dipole surround speakers radiate sound both toward the front and rear of the room, with minimal coverage at the listening position. This residential surround format is intended to replicate the surround soundfields in commercial cinemas, which use multiple monopole surrounds.

The monopole or bipole surround format uses additional speakers that match the left/center/right speakers for the left and right surrounds. Additionally one can further expand the surrounds with a rear surround and an overhead loudspeaker, for multichannel music, as well as with movies. This matching 7 speaker (plus additional subwoofers) arrangement is what *WSR* was interested in implementing in their new laboratory.

There are many important questions in home theatre design. What size room is best? What are the best locations for the main speakers, subwoofers and listeners? How does one control the low frequency response in a room with so many woofers? What surface treatment should be used on the front, left, right, rear walls and ceiling? There are also many additional questions about HVAC design, ergonomics, lighting, soundproofing, etc. that will not be discussed in this article.

In my opinion, today's new acoustic tools, coupled with existing home theatres electronic hardware and advanced projection systems, can make the home theatre experience as enjoyable, and in many instances more enjoyable, than a commercial movie theatre. Also remember that as the cost of home entertainment increases, it is even more important not to compromise the electronics with poor acoustical design. Good acoustical design provides an effective and aesthetic approach to realize the full potential of the electronic hardware so that audiophiles and videophiles can Listen To The Music, Not The Room!™

Room Reflections Cause Acoustic Distortion

The home theatre is essentially a "small" room acoustically. The volume is approximately 3,000- 6,000 cubic feet (85-170 cubic meters). The decay time is roughly 100 to 400 ms. The room's acoustical signature is strongly characterized by its low-frequency modal response and speaker-boundary interference, strong early reflection interference from surfaces, furniture and equipment racks, flutter echoes from untreated parallel reflective surfaces, sparse late reflection density and spatiality leading to poor sound diffusion and envelopment.

When the sound from a loudspeaker encounters the boundaries of a room, a very complex series of reflections occur. It is very difficult to isolate the direct sound alone, because these indirect reflections interact with it and among themselves to produce a wide range of effects, which we will call "Acoustic Distortion." If proper acoustic design is not utilized, a room may introduce sonic distortion that prevents the listener from hearing all of the detailed information the loudspeakers and electronics are capable of delivering. We need to be as mindful of acoustic distortion as we are about electronic distortion and reduce both of them to appropriate levels.

The sound that we hear in a critical listening room is determined by the complex interaction among the quality of the electronics, the quality and placement of the loudspeakers, the hearing ability and placement of the listener, the room dimensions (or geometry if non-cuboid) and the acoustical condition of the room's boundary surfaces and contents. All too often these factors are ignored and emphasis is placed solely on the quality of the hardware and loudspeakers. However, the tonal balance and timbre of a given loudspeaker can vary significantly, depending on the placement of the listener and loudspeaker and the room acoustic conditions. In some cases, the differences between different loudspeakers located in the same location in a room can be less than the differences introduced by moving the same loudspeaker to different locations in a room.

The acoustic distortion introduced by the room can be so influential that it dominates the overall sonic impression. The causes of acoustic distortion are:

1. Modal Coupling—the acoustical coupling between the loudspeakers and listener with the room's modal pressure variations or room modes
2. Speaker-Boundary Interference—the coherent interaction between the direct sound and the omnidirectional early reflections from the room's adjacent boundaries
3. Comb Filtering—the coherent constructive and destructive interference between the direct sound and early reflections
4. Poor Diffusion—the sparse spatial and temporal reflection pattern due to mid and late arriving reflections

Remember, dollar for dollar the acoustical treatment of your room will make more of an audible difference than any piece of electronic hardware, speaker, or cable. The goal of this article is to collect all of this information in one place and attempt to raise the reader's awareness of the potential acoustical problems in the rooms so that they can take measures to compensate for these sources of acoustical distortion.

Sources Of Acoustic Distortion

Room Modes

All mechanical systems have natural resonances. These resonances are one aspect that differentiates acoustic instruments. In rooms, sound waves coherently interfere as they reflect back and forth between hard walls. This interference results in resonances at frequencies determined by the geometry of the room. In completely reflective rectangular (cuboid) rooms, where the normal component of the particle velocity is

zero at the surface, the modal frequencies, associated with the eigenvalues of the wave equation, are determined by Eq. 1.

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

Equation 1

n_x, n_y and n_z are non-negative integers, L_x, L_y and L_z are the length, width and height of the room and c is the speed of sound. These modal frequencies are distributed among axial modes involving two opposing surfaces (e.g. n_x=1, n_y=0, n_z=0), tangential modes involving 4 surfaces (e.g. n_x=1, n_y=1, n_z=0), and oblique modes involving all surfaces (e.g. n_x=1, n_y=1, n_z=1).

For an axial mode between two opposite boundaries, this frequency is equal to the speed of sound, c, divided by twice the room dimension in that direction. For example, for c = 1,130 ft./sec, a 15 foot wall to wall dimension results in a first-order fundamental room mode of 37.6 Hz.

As an example, in Figure 1 we present the measured modal frequency response of a room whose length is 15 feet. The loudspeaker was located in a corner and the microphone was placed against a wall perpendicular to the 15 foot dimension, in order to record all axial modes. The first-order (100), second-order (200) and third-order (300) modes are identified in Figure 1 at 37.6 Hz, 75.3 Hz and 113 Hz, respectively. As the frequency increases, room modes are still present, but their number and density increase are not perceived as a problem.

Each of these modal frequencies has an associated three-dimensional pressure distribution in the room. In Figure 2, we present a two-dimensional illustration of the pressure distribution perpendicular to the length of the room, which is normalized to one and shown as a fractional coordinate. The numbers nx, ny and nz indicate the number of nodal planes of zero sound pressure perpendicular to the x-axis, y-axis and z-axis. In this example, ny and nz are zero and nx takes the value 1, 2 and 3. Notice the (100) mode has one nodal plane in the middle of the room (0.5), the (200) has two and the (300) has three perpendicular to the 15 foot length x-axis. Thus, in addition to choosing dimensional ratios that uniformly space the modal frequencies, we must consider how the listener and loudspeakers couple with the modal pressures that exist at the locations of the listener and loudspeakers.

Since conventional closed or ported dynamic loudspeakers are pressure sources, they will couple most efficiently when placed at a high pressure region of the modal or sometimes called standing-wave pressure distribution. The loudspeaker placement will

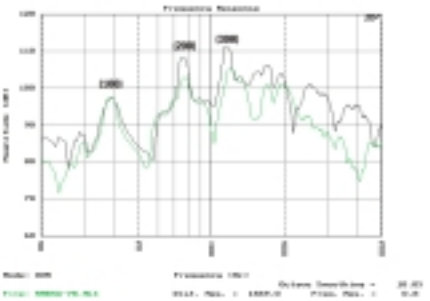


Figure 1. Measured modal frequency response in a room 7.5'(W) x 15' (L) x 9' (H). The (100), (200), and (300) modes are identified.

accentuate or diminish the coupling with the modal pressure variations at each of the modal frequencies. Similarly, a listener will hear different modal emphasis depending on where he or she is seated. Figure 2 illustrates how the sound energy is distributed along a room dimension. Examining Figure 2 reveals that the fundamental has no energy in the center of the room. Physically this means that if you were sitting in the middle of the room you would not hear this frequency. The first harmonic, however, is at a maximum. It can be inferred from this plot that, in the center of the room all odd harmonics are absent and all even harmonics are at a maximum. This is an important fact when considering the optimum listening position in a room as described later. The position of a listener's ear and loudspeaker with respect to these pressure variations will determine how they couple with the room. Most home theatres are rectangular simply because they are converted bedrooms, offices, garages, etc. Since they are rectangular we can calculate the modal frequencies and pressure distributions. Once they become non-rectangular, none of this simple math applies. Therefore, one must determine the best room dimensions that offer the flattest modal response and the best positions to locate the loudspeakers and listeners to optimally couple with the pressure response of the room. This problem has now been solved for rectangular rooms using a software program called the Room Sizer™ that combines image modeling and multi-dimensional optimization techniques described later in the discussion.

Speaker-Boundary Interference Response

Room modes develop as reflected sound interferes with itself. This next type of acoustic distortion is due to the coherent interference between the omnidirectional direct sound of a loudspeaker and the reflections from the room, in particular the corner immediately surrounding it.

This distortion occurs across the entire frequency spectrum, but is more significant at low frequencies. We refer to it as the

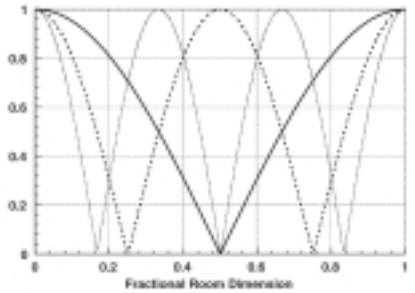


Figure 2. Normalized energy distribution of the first three modes in a room. 0.5 is midway between two opposite walls (0 and 1)

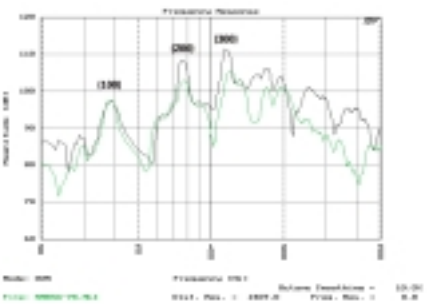


Figure 3. Sound from real and virtual speakers combine to create the speaker/boundary interference response.

Speaker Boundary Interference Response or SBIR. The room's boundaries surrounding the loudspeaker mirror the loudspeaker forming virtual images. When these virtual loudspeakers (reflections) combine with the direct sound, they can either enhance or cancel it to varying degrees depending on the phase relationship between the reflection and direct sound at the listening position. In Figure 3 a loudspeaker is located 3 feet from each room surface with coordinates (3,3,3). The four virtual images on opposite sides of the main room boundaries that are responsible for first order reflections are also shown. A virtual image is located an equivalent distance on the opposite side of a room boundary. The distance from a virtual source to the listener is equal to the reflected path from source to listener. In addition to the four virtual images shown, there are 7 more. Three virtual images and 1 real image in the speaker plane and 4 virtual images of these above the ceiling and floor planes. Imagine that the walls are removed and 11 additional physical speakers are located at the virtual image positions. The resultant sound at a listening position would be equivalent to the sound heard from one source and 11 reflections!

The effect of the coherent interference between the direct sound and these virtual images is illustrated in Figure 4. The SBIR is averaged over all listening positions with the

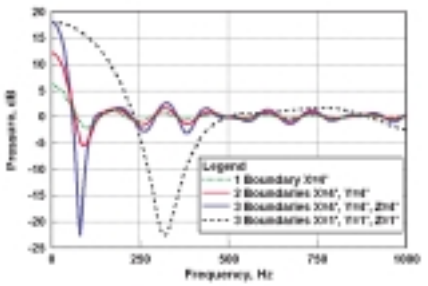


Figure 4. Speaker-Boundary Interference Response for several loudspeaker positions near a corner.

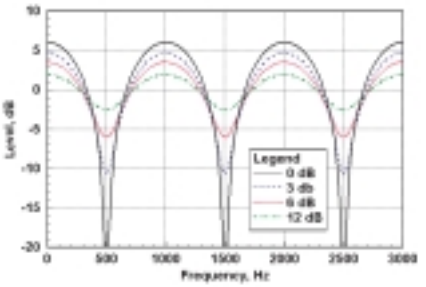


Figure 5. Comb filtering with 1 one reflection delayed by 1 ms with attenuated of 0, 3, 6 and 12 dB relative to the direct sound.

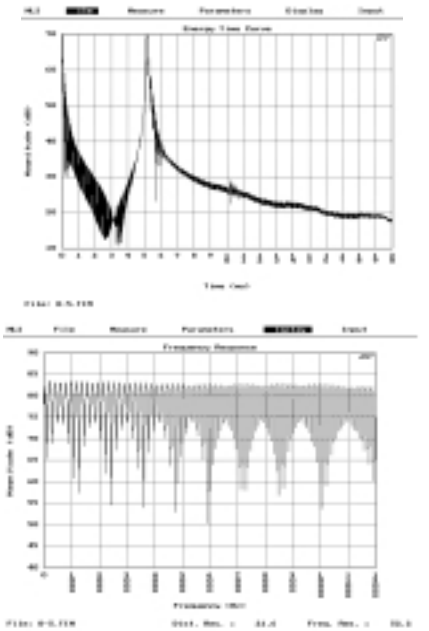


Figure 6. Time (upper) and frequency (lower) response of the direct sound combined with a side wall reflection. The comb filtering is apparent

speaker located 4 feet from one, two and three walls surrounding the loudspeaker. It can be seen that as each wall is added, the low frequency response increases by 6 dB and the notch, at roughly 100 Hz, gets deeper. It is important to note at this point that once this notch is created, due to poor placement, it is virtually impossible to eliminate without moving the listener and loudspeaker, since it is not good practice to electronically compensate for deep notches. Thus the boundary reflections either enhance or cancel the direct sound depending on the phase relationship between the direct sound and the reflection at the listening position. Initially, the direct sound and reflection are in phase and they add. As the frequency increases the phase of the reflected sound lags the direct sound. At a certain frequency the reflection is out of phase with the direct sound and a cancellation occurs. The extent of the null will be determined by the relative amplitudes of the direct sound and reflection. At low frequencies there is typically very little absorption efficiency on the boundary surfaces (especially if only thin porous absorption is being utilized) and the notches can be between 6 and 25 dB! The low frequency rise in Figure 4 illustrates why one can add more bass by moving a loudspeaker into the corner of a room. The challenge of finding the optimum location for many loudspeakers in a room is a multi-dimensional optimization analysis; i.e. there are simply too many variables to try by trial and error. This problem has now been solved for rectangular rooms using a new software tool called the Room Optimizer® described later.

Comb Filtering

Another form of acoustic distortion introduced by room reflections is comb filtering. It is due to interference between the direct sound and a reflected sound. In critical listening rooms, we are primarily concerned with the interaction between the direct sound and the first-order (i.e. single-bounce) reflections. Reflections cause time delays, because the reflected path length between the listener and source is longer than the direct sound path.

Thus, when the direct sound is combined with the reflected sound, we experience notches and peaks referred to as comb filtering, because they resemble a series of equally spaced notches like the teeth of a comb. The reflections enhance or cancel the direct sound to varying degrees depending on the phase (path length) difference the reflection and the direct sound at the listening position. An example of comb filtering between the direct sound and a reflection delayed by 1 ms is shown in Figure 5. Four conditions are illustrated. 0 dB refers to the theoretical situation in which the reflection is at the same level as the direct sound. The remaining three interference curves indicate situations in which the reflection is attenuated by 3, 6 and 12 dB. The location of the first notch is given by the speed of sound divided by 2 times the total path length difference. The spacing between subsequent notches is twice this frequency.

The audible effect of comb filtering is easy to experience using a delay line. If you combine a signal with a delayed version, you will experience various effects referred to as chorusing or flanging, depending on the length of the delay and the variation of the delay with time. Shorter delays have wider bandwidth notches and thus remove more power than longer delays. This is why microsecond and millisecond delays are so audible. The effect of a reflection combining with the direct sound is illustrated in Figure 6. The upper curve shows the arrival time of both the direct sound and the reflected sound. The lower curve shows the severe comb filtering that a single reflection introduces. If your speaker had a free-field response like this lower curve, you probably would not have purchased it! Yet, many rooms are designed without reflection control. In reality, our ear/brain combination is more adept at interpreting the direct sound and reflection than the FFT analyzer, so that the effect may be somewhat less severe. Comb filtering is controlled by attenuating the room reflections or by controlling the loudspeaker's directivity to minimize boundary reflections. If the loudspeaker has constant directivity as a function of frequency, then broad bandwidth reflection control is necessary. Since the directivity of conventional loudspeakers increases with frequency, low frequency reflection control is important. For this reason, one would not expect to control low frequency comb filtering effects with a thin porous absorptive foam or panel. Comb filtering can be controlled by using absorption, which removes energy from the room, or diffusion, which distributes the reflection over time, with minimal absorption. Both approaches are valid and produce different psychoacoustical reactions. Using absorption to reduce the effect of a specular reflection will produce pinpoint spatial phantom images. On the other hand, diffusion will produce sonic images with more spaciousness (width, depth and height).

Poor Diffusion

While many readers may have had some introduction to modal coupling, the speaker-boundary interference and comb filtering, diffusion is probably a new concept. It is also a complicated concept and there is much confusion about diffusion. Diffusion is especially important in surround sound formats, as the goal is to provide an enveloping and realistic experience in which the listener is immersed in the visual and aural event.

Figure 7. A diffusing surface with phase variation in only one direction scatters incident sound into a hemidisc for a given angle of incidence

Figure 8. Hemispherical scattering pattern from a diffusing surface with phase variation in two directions for any angle of incidence

Figure 9. The first 3D diffusion coefficient measurement goniometer. The red sample is at the origin of an inner microphone semicircle and the loudspeaker is positioned on the outer semicircle in the upper right

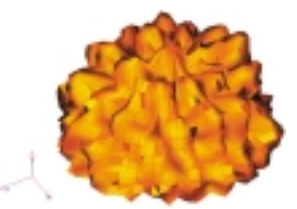


Figure 10. Measured polar balloon representing diffuse sound from a Skyline® diffusor for normal incidence at the 2 kHz third-octave band

First we should draw a distinction between spatial diffusion and surface diffusion. When acousticians mention diffusion, they are usually referring to spatial diffusion. The ideal case being a diffuse soundfield, in which the sound energy is not only distributed equally over all positions, but is also propagating or flowing equally in all directions. This doesn't mean that each listener hears the same total loudness, because the direct sound decreases as the distance from the sound source increases. But by achieving an even reflected energy around the room, problems caused by too much or too little reflected sound are avoided.

Surface diffusion, on the other hand, does not refer to the diffusive properties of a space, but rather refers to a surface's ability to uniformly scatter sound. In Figure 7 we show how a diffusing surface with phase (depth) variation in only one direction scatters incident sound into a hemidisc for a given angle of incidence. Figure 8 illustrates the hemispherical scattering pattern from a diffusing surface with phase variation in two directions for any angle of incidence.

For the past 100 years, since the founding of architectural acoustics by Sabine, the acoustical community has concentrated on designing, measuring and standardizing the performance of sound absorbing surfaces. In 1983, RPG introduced the first designable, commercial, diffusor based on mathematical number theory and developed the first 2D goniometer to measure and characterize these new surfaces. Since then there has been growing interest in measuring and characterizing the performance of scattering surfaces and the AES formed a working group SC-04-02, which I have chaired since its inception, to study the problem. I am personally gratified to report that after 17 years of research an information document (AES-4id-2001) describing the measurement of the diffusion coefficient is now published. The first 3D goniometer used to characterize diffusing surfaces is shown in Figure 9. The goniometer measures the scattered sound over the surface of a hemisphere and the first representation of this diffuse scattering at 2 kHz is shown for the Skyline® in Figure 10. For more information also visit http://www.rpginc.com/research/index.htm).

Now that we are gaining a better understanding of how to design and measure diffusing surfaces, it is only prudent to try to use all of the tools in the acoustical palette, namely absorption, reflection and diffusion in the design of critical listening rooms and performance facilities.

The role of diffuse reflections in concert hall acoustics has been of interest for many years. This interest being partly fueled by the fact that some of the oldest halls with the best reputations contain highly diffusive surfaces in the form of statuary, surface relief ornamentation, etc. Small room acoustics in critical listening music reproduction spaces is very different than larger music production spaces. Research has established the psychoacoustic relationship between reflection level, reflection time delay and subjective impressions of coloration (comb filtering), image shifting and spreading, spaciousness, acoustic glare and echo disturbance. This research has also established the threshold of detection for reflections arising from certain directions and from various sources including speech, impulses, pink noise, and music in a variety of anechoic and reflective environments. The reader also is directed to a book by F. Alton Everest entitled the *Master Handbook Of Acoustics*, Fourth Edition, McGraw Hill, for further detailed information. Because of the proximity of the boundary surfaces to loudspeakers and listeners in small rooms, reflection control is important. Room reflections can be attenuated by absorption, redirected by reflection and uniformly distributed by diffusion. Thus, we have three surface treatment tools to attempt to create an appropriate time signature (impulse response) and a diffuse soundfield in small rooms to the best extent possible. In Figure 11, we show the energy time curve for a small room before (top) and after (bottom) acoustical treatment. The top curve illustrates the direct sound, interfering sidewall, floor and ceiling reflections and sparse room reflections arriving after the rear wall reflection at roughly 19 ms. The side wall,

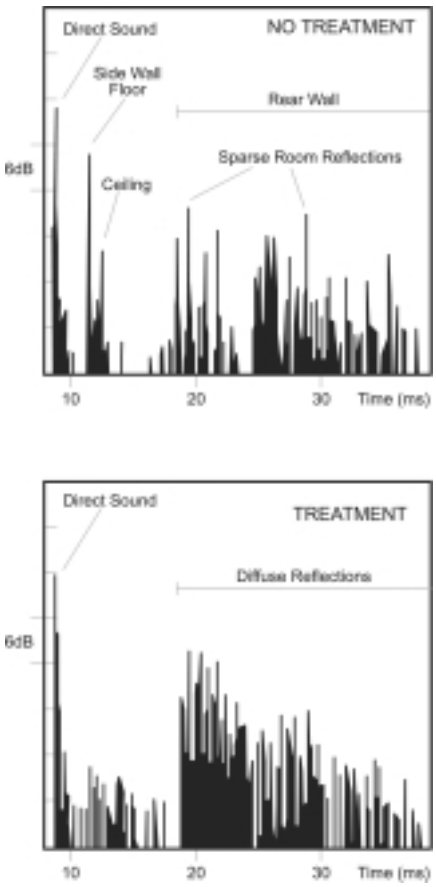


Figure 11. Time response for a critical listening room without any acoustical treatment (top) and after application of acoustical treatment. Note minimization of interfering sidewall, floor and ceiling reflections and increased reflection density following the rear wall reflection at about 18 ms

FREQUENCY	ACOUSTIC DISTORTION	
	PROBLEM	SOLUTION
Below 300 Hz		
	Modal Response	1. Room Dimensions 2. Speaker/Listener Placement 3. Damping 4. EQ
	Speaker-Boundary Interference	1. Speaker/Listener Placement 2. Damping 3. EQ
Above 300 Hz		
	Comb Filtering	1. Absorption 2. Diffusion 3. Surface Treatment Placement
	Poor Diffusion	1. Diffusion 2. Reflection 3. Surface Treatment Placement

Table 1. List of the causes of Acoustic Distortion and possible solutions below and above 300 Hz

floor and ceiling reflections were minimized using absorption and the reflections following the temporal reflection free zone (RFZ™) or initial time delay gap were diffused by application of reflection phase grating diffusors on portions of the rear wall. The diffusors transformed the sparse room reflections into a dense reflection pattern with a uniform linear decay, characteristic of a diffuse sound field.

Acoustical Solutions

Now that we have discussed the four forms of Acoustic Distortion, namely modal coupling, speaker-boundary interference, comb filtering and poor diffusion, we can begin to consider ways in which to minimize these effects and design a critical listening room or home theatre.

We can summarize the potential acoustic distortion problems and possible solutions, Table 1, by dividing the frequency range roughly at 300 Hz. Below 300 Hz we need to focus on the coupling between the loudspeakers and listener with the modal response of the room and the interference at the listening position between the loudspeakers and their adjacent boundaries. The modal response can be optimized by utilizing optimized room dimensions, proper placement of the loudspeakers and listener, use of dedicated low frequency absorption (damping) in the proper frequency ranges and fine-tuning with electronic equalization. The speaker-boundary interference can be minimized by proper placement of the loudspeakers and listener in the room, appropriate low frequency absorption (damping) and fine-tuning with electronic equalization. Above 300 Hz we are dealing with specular reflection effects which result in comb filtering and the lack of adequate sound diffusion. Comb filtering can be minimized through the strategic application of absorptive, diffusive, abffusive or diffsorptive™ surface treatment. Sparse diffusion can be improved through the application of efficient diffusive surfaces and a coupling of reflective and diffusive surfaces strategically placed.

We now begin a methodical discussion of the various solutions we have at our disposal to minimize Acoustic Distortion.

Low Frequency Control <300Hz: A New Approach to Sizing Small Critical Listening Rooms

Modes in small rooms often lead to extended sound decays and uneven frequency responses. The problem arises at low frequencies because of the relatively low modal density. Many methods and optimum room ratios have been suggested over the years to minimize coloration. Essentially these methods try to avoid degenerate modes, where multiple modal frequencies fall within a small bandwidth, and also bandwidths with absences of modes. The starting point for these previous methods to determine room dimensions, is usually the equation defining the eigenfrequencies within a rigid rectangular enclosure, Equation 1. The eigenfrequency solution is only applicable for rigid surfaces.

RPG has developed a new approach that automatically determines optimal room dimensions in rectangular rooms given an absorption coefficient for each surface and a minimum and maximum dimensional range for the length, width and height. The new method uses a theoretical model, which although not perfect, is a more accurate model of low frequency room behavior than the simple eigenfrequency solution. The new method addresses the shifting of resonant frequencies due to absorption. Since conventional approaches usually group resonances into third-octave bands, shifts due to absorption may result in incorrect assignment. Another effect of absorption is that it acts differently on axial, tangential and oblique modes—for example, axial modes will have the greatest magnitude and least damping. None of the previous methods account for this fully. A further difficulty with previous methods is the choice of criterion used for evaluation. For example, Bonello's method makes several assumptions—such as the use of a one-third-octave bandwidth, and that five modes in a bandwidth mask the effects of coinci-

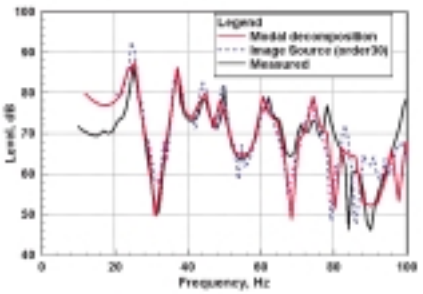


Figure 12. Comparison between measured modal response (solid black line) and the predicted response based on modal decomposition (solid red) and the image source method (dotted blue).

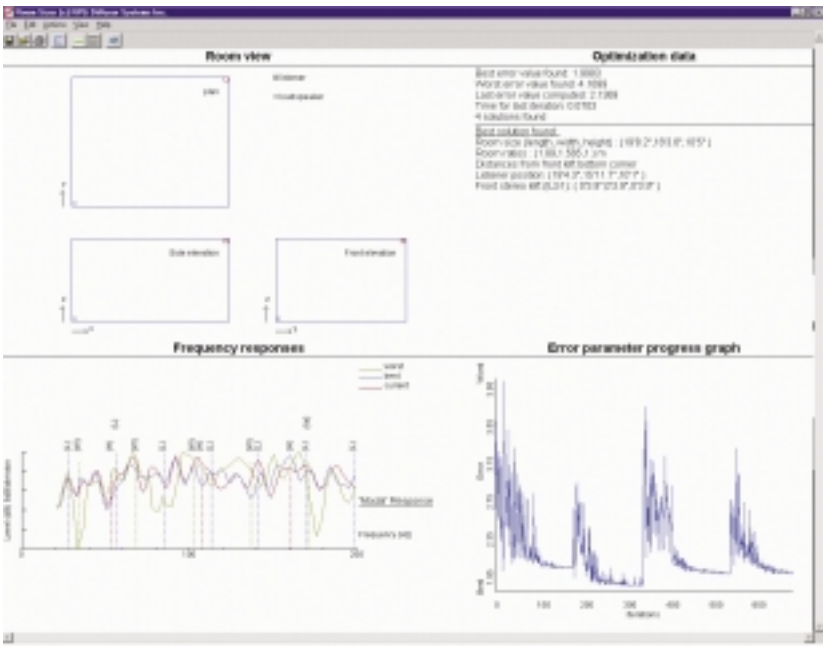


Figure 13. Screen shot of the Room Sizer™ software illustrating the Room View (upper left), the Optimization Data (upper right), the modal responses (lower left) for the current, best and worst solution found thus far and the error parameter progress graph evaluating the merit of the dimensions examined versus the number of iterations

dent modes—which are empirical rather than fundamental in nature. The new method acts directly on the modal response of the room, so a criterion based on mode spacing is no longer required. This is an improvement, because the mode spacing is one level more removed from the actual signals received by the listener than the modal response. The new method is based on producing the flattest possible modal frequency response for the room. It uses an optimizing computer algorithm to search for the best solutions. A more detailed description of previous methods and a technical description of the new approach called the Room Sizer is given in a technical paper available in RPG's Acoustics Library at http://www.rpginc.com/news/library.htm.

Figure 12 compares measurements in a listening room to a modal decomposition model and an image source model, which are equivalent in rectangular rooms. The listening room has dimensions 6.9m x 4.6m x 2.8m. Below 100 Hz, good agreement between the models and the measurement are shown. Slightly better agreement can be achieved at the expense of speed of the optimization. The agreement between theory and experiment is also dependent on properly deconvolving loudspeaker response. The sound power of the loudspeaker is difficult to measure, as it is difficult to get anechoic conditions down to 20 Hz in normal test chambers.

The user inputs minimum and maximum values for the length, width, and height (which can be the same if fixed), and the Room Sizer finds the best dimensions within these limits. The program predicts the modal response of the room and rates the quality based on the squared deviations of the modal response from a least squares straight line. This parameter is used because it is assumed that slow variation in the spectrum can be normalized out by simple equalization, and what is important is to reduce large local variation. The program then tries other dimensions trying to find those that have the lowest squared deviations or the flattest response. A simplex search engine was used to find the best room dimensions. In the Room View (upper left) of Figure 13, the speaker and loudspeaker are shown in opposite diagonal corners. The Optimization data, including the standard deviation and room dimensions, are listed in the upper right. The frequency responses for the current, best and worst dimensions found are shown in the lower left, with the positions of the length (L), width (W) and height (H) predicted by Equation (1) indicated by dotted vertical lines. The Error parameter progress graph in the lower right illustrates the standard deviation (error) for the various iterations (trial room dimensions). The best solution will have the lowest error. Four solutions are illustrated, with solution two exhibiting the best performance.

The Room Sizer offers a simpler and more accurate approach to room dimensioning than the spreadsheet solutions offered by some of the music industry magazines and we urge the industry as a whole to investigate this new approach. In the *WSR* laboratory as in many rooms, there were constraints on the minimum and maximum dimensions. The ranges for the length, width and height were 26 feet – 28 feet, 21 feet – 21 feet 11 inches and 13 feet – 14 feet, respectively. As seen in Figure 14, the Room Sizer calculated dimensions that are an improvement over the popular Louden and Golden Mean ratios. The optimum dimensions for this case were 26 feet x 21 feet 9 inches x 14 feet. Also be aware that the Room Sizer allows for the use of electronic equalization by minimizing the dips in the modal response at the expense of the peaks, which are more amenable to equalization.

Have some fun and download a free Room Sizer demo at http://www.rpginc.com/products/roomsizer/index.htm.

Listener/Loudspeaker Placement

The Room Sizer minimizes the standard deviation of a "fully excited" modal response, with the source in one trihedral corner and the listener in an opposite corner. Now not many people listen to surround sound using this configuration, but it does fully excite the modal response of the room and allows us to obtain the best room dimensions. Once we have built a dimensionally optimized room, what is the best location for the loudspeakers and listener?

While it is important to provide uniform modal frequency distribution by optimizing the dimensional room ratios, the degree of acoustic gain at each frequency depends solely on the location of the listener and loudspeakers with respect to the room's sound pressure distribution at that frequency. Thus, even if the room dimensions are "ideal" according to some criteria, only proper positioning of the listener and loudspeakers can minimize low frequency acoustic distortion. In conventional

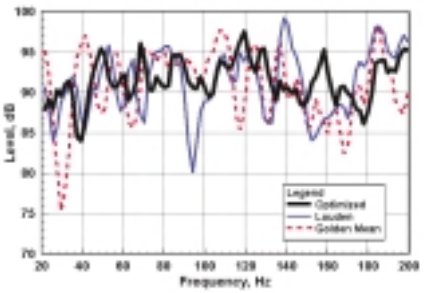


Figure 14. Comparison of the Optimized modal response predicted by the Room Sizer™ with dimensions suggest by Louden and the Golden Mean

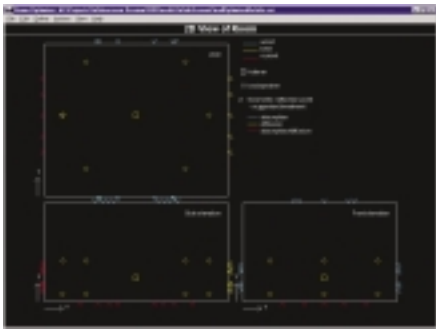


Figure 15. Optimized locations for the front and rear left/center/right loudspeakers and listener

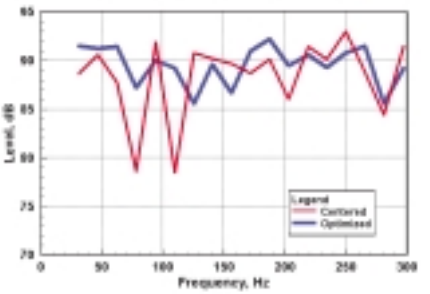


Figure 16. SBIR comparison between simple centering of the loudspeakers/listener in the room and optimal placement

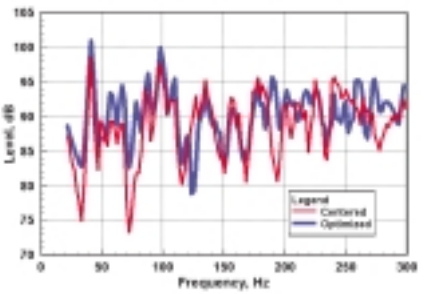


Figure 17. Modal response comparison between simple centering of the loudspeakers/listener in the room and optimal placement

approaches, it is impossible to arrive at an optimum solution by treating the speaker boundary interference response (SBIR) and the modal coupling independently, because minimizing the speaker boundary interference may not optimize the modal coupling at all frequencies and vice versa. Thus, the need for an automated, computerized, multi dimensional optimization approach becomes necessary. Room Optimizer® is the industry's first Windows program that automatically and simultaneously optimizes the SBIR and modal coupling. The program utilizes modern geometrical image model prediction techniques along with powerful multi dimensional optimization to achieve the smoothest and flattest bass response in a rectangular room. This result is accomplished quickly, effectively, and automatically by properly positioning the listener and loudspeakers. In addition to optimizing the bass response, the program also calculates first order reflection positions for mid to high frequency acoustical surface treatment discussed later.

With the computational desktop power now available, sophisticated positioning and evaluation algorithms can be used to automatically search for the best listener and low frequency loudspeaker positions in a rectangular room. First, a random set of listener and loudspeaker locations is evaluated by calculating the energy impulse response via an image model. Then, two FFTs are performed on the impulse response to reflect the transient and long-term aspect of the way we perceive music. A windowed 65 ms short term FFT of the low order reflections determines the speaker boundary interference response (SBIR). A long term FFT of the entire windowed impulse response extending to 15 or more reflection orders determines the "modal" response. A weighted sum of the standard deviation of each response over a definable low frequency range, typically between 20 to 300 Hz, is determined. If the error is below the specified tolerance, the program ends. If the error is above this tolerance, the optimization enters a simplex search routine that suggests the next potentially best trial locations and the process is repeated. This iterative process continues until the program finds the listener and loudspeaker locations with the smoothest and flattest combined spectra. A technical description of the Room Optimizer can be obtained in RPG's Acoustics Library at http://www.rpginc.com/news/library.htm. Have some fun and downward a free demo version of the Room Optimizer at http://www.rpginc.com/products/roomoptimizer/index.htm

The program offers a powerful feature that allows the use of symmetry and displacement relationships between independent and dependent speakers to speed the automated search for the global minimum. For example, in the *WSR* case, each loudspeaker had two woofers symmetrically displaced 28 inches above and below the centrally located tweeter. If we define the lower left tweeter as an independent driver, we can determine the position of the upper woofer by a vertical translation of 56 inches. Similarly, if the left front and right front speakers are symmetrically placed about the plane containing the listener, then the right lower and upper woofer can be described by mirror symmetry across the listener plane. In the *WSR* room, 13 of the 14 woofers can be described by translation and symmetry operations on the lower left front woofer.

The user is also given the opportunity to limit the search range for the listener and loudspeakers. This makes it possible to find the best locations for a given room, even though this solution may not be the mathematically best answer. The limits of the listener and independent loudspeakers are defined in terms of rectangular volumes, determined by the minimum and maximum coordinates. To include the lessons we have learned about good imaging, the program allows the user to define the angle formed between the listener and lines to the front left and right speakers.

In the *WSR* laboratory, we made use of all of these tools. The distance between listeners and loudspeakers was constrained to be as close to 10 feet as was possible. The angle between listener and left/right front, left/right rear, front/rear right, and front/rear left were constrained to be as close to 90 degrees as possible. The search ranges for the listener and loudspeakers were limited because the room was marginally large enough to contain this listening geometry. The program was also allowed to move this constrained hemispherical collection of loudspeakers and listener off center front/back and left/right to determine the flattest room response. The final orientation is seen in Figure 15. The carpeting was used to accentuate these optimized loudspeaker and listener positions. Typical examples of improvement can be seen in Figure 16 and Figure 17, for the speaker/boundary interference and modal responses, respectively. The comparisons are between simply centering the hemisphere in the room (Centered) and optimizing the placement (Optimized). Once the listening position is determined using the main speakers, the program can also provide optimization of subwoofers via a separate optimization over the 20-80 Hz frequency range (or whatever the operating range is).

Low Frequency Absorption

The remaining low frequency control tools are dedicated low frequency absorption and equalization. To obtain low frequency absorption one can use thick porous absorption with large cavity depths or resonant absorbers. Thick spaced porous absorbers are effective, but one must control the mid-high frequency absorption, which also will be present. While there are many equations for Helmholtz and diaphragmatic resonant absorbers, do-it-yourselfers are warned that one must determine not only the resonant frequency, but also the Q or width of absorption and the efficiency of absorption. PG has developed a wide range of pressure transducer membrane absorbers, called Modex™, that offer 100 percent absorption at 40, 50, 63, 80 and 100 Hz. These membranes are designed and tested in a 7 ton, 2x2x24-foot long impedance tube, because the standard rev room C423 test is only valid down to 100 Hz. Readers can find out more about these devices at http://www.rpginc.com/products/modex/index.htm.

Because of the requirement for variability in the *WSR* laboratory, the VariScreen™ was chosen to address low frequency absorption as well as controlling comb filtering and offering diffusion (discussed next). It allows the low frequency room response to be manually tailored as desired by adjusting the angle and distance of the VariScreen to the wall. A description can be seen in Figure 18, where the low frequency absorption increases as we open the VariScreen from bottom to top of the illustration. Remember that the efficiency of a porous absorber is highest when the sound is traveling at its highest velocity (2.5 feet from a wall for 100 Hz). Unfortunately, at the wall surface where porous absorbers are usually placed, the particle velocity and hence the absorption efficiency is zero!

The VariScreen, shown in Figure 19, is a two sided, hinged, rollable, and freestanding screen. One side offers pure absorption and the other side is diffsorptive. The diffsorptive side can be used to face into the room and thus attenuate the high frequency absorption above 1000 Hz as seen in Figure 20.

Electronic Equalization

In a home theatre, the listener is typically located in the direct field within the critical distance (that point at which the direct and reverberant sound are at the same level). In this case, full bandwidth electronic equalization to compensate for room problems may not be advisable, as it may corrupt the one thing that may be acceptable in the room, namely the frequency response of the direct sound! Therefore, prudence dictates

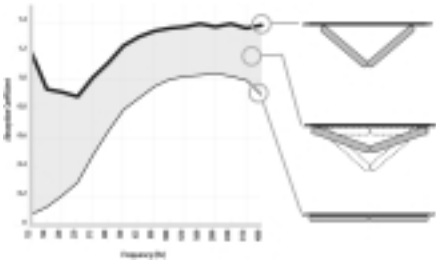


Figure 18. One can adjust the angle of the VariScreen™ to provide the low frequency absorption desired

Figure 19. Photo of VariScreen™

that mid/high frequency equalization be applied by a trained acoustician. On the other hand, there may be valid reasons to introduce low frequency electronic equalization to complete the adjustment of the low frequency room response. Psychoacoustically, the effect of room modes on the effective output power of the loudspeaker is essentially indistinguishable from a real departure of the loudspeaker from a level response. Low frequency equalization below roughly 300 Hz is justifiable when, for practical reasons, one cannot relocate the listening position or loudspeaker positions or to fine tune the room's low frequency response.

Mid-High Frequency Control > 300 Hz Comb Filtering And Poor Diffusion:

Above 300 Hz reflections may be controlled using strategic placement of absorption, diffusion or diffsorption around the specular reflection position. This is the location on a boundary surface at which the angle of incidence equals the angle of reflection. Imagine all wall surfaces are covered with mirrors. Any locations on the

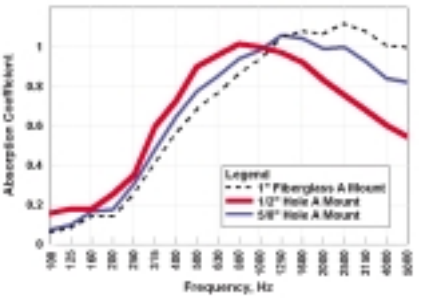


Figure 20. BAD panel attenuates high frequency absorption and diffuses this energy

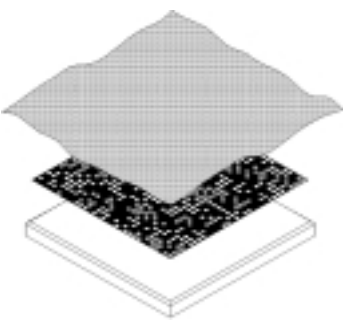


Figure 21. Application of the BAD™ template over a porous absorber and covered with a decorative fabric

room's surfaces at which a listener sees a loudspeaker is a potential location for an absorber, diffusor or diffsorber. In the *WSR* laboratory, the requirement for variability, a live but controlled ambiance and envelopment led to the selection the VariScreen and Skyline diffusor. Some experiences with these devices by professional engineers can be found at http://www.rpginc.com/news/news9911.htm, http://www.rpginc.com/news/news0009.htm and http://www.rpginc.com/ news/news9808.htm.

The approach was to use the VariScreens freestanding in front of the walls, augmented by Skylines diffusors as needed, which simply attach to the surface. A freely suspended cloud was chosen as the ceiling design element, because of the flexibility it offered and because of the ease in mounting Skyline diffusors, lighting and a fabric covered opening for the overhead speakers.

Walls

Because of the variability required in the *WSR* laboratory, we chose the VariScreen for wall treatment. It consists of a purely absorptive side and diffsorptive side. The diffsorptive side is formed from a patented flat binary amplitude diffsorber, affectionately known as a BAD™ panel. The BAD panel was designed to mitigate the disproportionate absorption of thin fabric wrapped panels at high frequency, as seen in Figure 22. The BAD panel provides diffusion by using

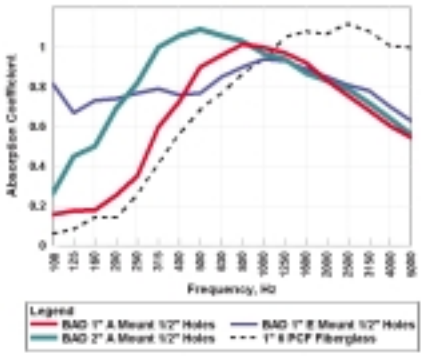


Figure 22. Absorption coefficient for the BAD panel side compared to 1-inch purely absorptive panel

a binary amplitude grating in the form of a perforated template placed between an absorptive panel and the decorative fabric covering, as seen in Figure 21. The binary amplitude grating is formed by mapping absorption to a zero and reflection to a one in a binary sequence. Thus, reflection plus absorption properly distributed equals diffusion. The binary template contains an irregular distribution of holes whose positions are determined by an optimal two-dimensional binary sequence. In Figure 22, it can be seen that above 1000 Hz, the 1-inch and 2-inch BAD panels have attenuated high frequency absorption and enhanced low frequency absorption compared to the 1-inch fabric wrapped panel. The high frequency energy, which is wasted with a fabric wrapped panel, is now diffused, adding life and ambiance to the room. Figure 23 illustrates how uniformly the BAD panel diffuses sound up to 20 kHz for angle of incidence of 0, 30 and 60 degrees. This type of performance is very well suited to home theatres to mitigate the "dead" sound, which is so prevalent and yet still provide reflection control. The mass of the template is designed to allow the BAD panel to transition to pure absorption at roughly 1000 Hz. The diameter of the holes determines the high frequency diffusion response, which is shown in Figure 23 to extend above 20 kHz.

WSR can select whichever surface is most appropriate for a given loudspeaker configuration simply by moving or rotating the panels. One of the benefits of this design approach is that the room is never locked in any one configuration. The side walls from 8 feet to 14 feet were left reflective so as not to overly damp the room.

Ceiling

The ceiling was also left reflective, however, a 16-foot x 16-foot cloud was suspended to a height of 10 feet. The cloud was used for many purposes and it is one of the authors favorite design elements.

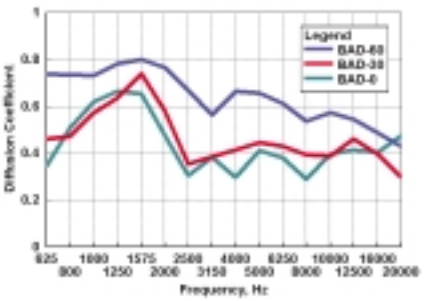


Figure 23. Illustration of the broad bandwidth diffusion of the BAD™ panel at incident angles of 0, 30 and 60 degrees

Another favorite is a wall-ceiling soffit, which was left as an option if needed. The cloud contained Skyline diffusors, shown in Figure 24, to provide envelopment and also give the room a more intimate scale than the 14-foot ceiling would have provided. The unique broad bandwidth diffusion of the Skyline is shown in Figure 25, averaged (mean) over all angles of incidence at 5-degree intervals and compared to the diffusion coefficient of a 2-foot x 2-foot flat panel of similar size. There are two mechanisms for sound diffusion—size diffraction and surface topology. You will notice that at about 565 Hz the two curves begin to deviate. This is a reality check on the experimental measurement, because size diffraction should end at a frequency roughly equal to the speed of sound divided by the size of the panel (1,130 ft./sec/2 feet= 565 Hz). As you can see up to 565 Hz scattering from a flat panel and a diffusor of similar size are equal as it should be. Above this frequency, the wavelengths are small enough to "see" the surface variation and begin to diffuse based on the nature of the surface topology. It is important to indicate that not any surface variation is acceptable. Diffusion involves constructive and destructive interference and this complex interaction is often non-intuitive. This is why we encourage everyone to request proof of performance testing for all absorptive and diffusive surfaces from manufacturers. Over the past 20 years, RPG has developed the ability to design, predict, measure, optimize and quantify the performance of absorptive and diffusive surfaces. We offer the world's largest selection of diffusive surfaces and invite you to visit www.rpginc.com to find one that might suit your needs.

The cloud also contained a center fabric covered opening 4 feet x 4 feet to conceal the overhead speaker. Very attractive perimeter lighting was provided to enhance the aesthetic appearance of the ceiling. Another advantage of the cloud is that it offers the opportunity to add statistical absorption on the top surface if the decay

Figure 24. Painted Skyline® in faux granite finish

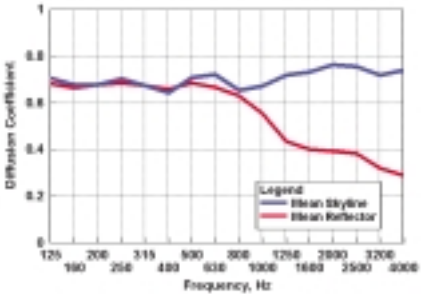


Figure 25. Comparison of the average incidence (mean) Diffusion Coefficient for a 2-foot x2-foot Skyline® and a flat panel of comparable size. At roughly 565 Hz, the diffraction limit, the Skyline begins to diffuse compared to the flat panel.

time of the room ever need adjusting.

Summary

Today's home theatres are taking advantage of significant advances in digital electronics as well as digital acoustics. The current state-of-the-art provides an impressively realistic enveloping and immersive audio/video experience. We have attempted to define the sources of acoustic distortion in home theatres and provide solutions to minimize these effects. In addition to room acoustics, home theatres require attention to sound isolation, ergonomics, architectural design, HVAC and a host of other factors. When undertaking an acoustical analysis of a room, consult an acoustician. These professionals have a wealth of experience that they can offer in the early stages that will save you time and money in the long run.

Below are Dr. Diffusor's top ten tips that will help you Listen To The Music, Not The Room!

1. Begin your design by addressing the potential forms of low frequency acoustic distortion. Determine optimum room ratios to uniformly distribute the room's resonant frequencies using the latest optimization soft-

ware. Build a rectangular sound isolation shell so you can predict modal response and add the desired architectural design inside of this.

2. Provide absorption extending down to the cutoff frequency of the woofers on wall surfaces contributing to modal emphasis as determined by a measurement, a listening test or a computer prediction.

3. Minimize the modal and speaker boundary problems by taking advantage of the latest image model/multi-dimensional optimization algorithms to insure that the loudspeakers, subwoofers and listening positions are in their optimum positions.

4. After acoustically addressing the low frequency response of the room, finalize low frequency tuning by using sparse amounts of electronic equalization below roughly 200 Hz if necessary.

5. Now address the room response above 300 Hz with surface treatments of absorption, reflection, diffusion, or diffsorption strategically placed.

6. Divide the wall surfaces vertically into thirds. Provide reflection or dedicated bass absorption on the lower third, use absorption, diffusion or diffsorption in the mid third to control reflections, use reflection, diffusion or bass absorption in the upper third.

7. If using dipole surrounds, keep the upper third of the room reflective or diffusive. If matching monopoles are used, diffuse the surfaces facing the surround channels to enhance envelopment.

8. Diffuse portions of the rear wall and ceiling with 1D or 2D diffusors.

9. Utilize wall-ceiling and wall-wall soffits whenever possible to provide low frequency absorption, lighting and conceal wiring and HVAC. Use ceiling clouds whenever possible to provide lighting, diffsorption and conceal HVAC and low frequency dedicated absorbers above.

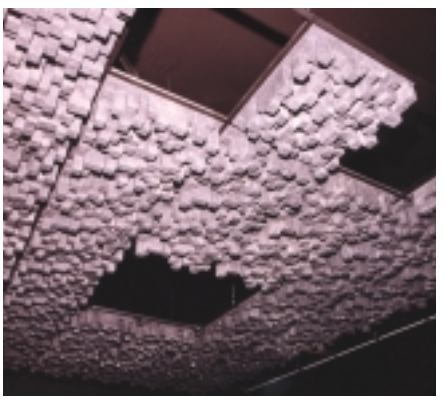
10. Measure the room's time and frequency response at several listening positions using any of the excellent transfer function or stimulus and response approaches. Analyze the results, acoustically tweak to taste and enjoy! ■

Prepping Of Skyline® Diffusors

Julio Ortez Installing Screen In Acoustical Cloud

VariScreens® Along Theatre Walls

Workers Installing Skyline® T-Bar Ceiling



Closeup Of Skyline® Acoustical Cloud

VariScreens® In Theatre Background

Worker Installing Skyline™ Ceiling Frame