Technical Bulletin on the Application of Diffusion in Critical Listening Rooms

by

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The sound that we hear in most environments is a combination of the direct sound and the indirect reflections from surfaces and other objects. Hence, one of the central topics in room acoustics is how to manipulate these indirect reflections that affect the way we perceive sound.

This technical bulletin attempts to answer the most frequently asked questions concerning diffusors and their application in the design of critical listening rooms:
- What is a diffusor?
- How do diffusors scatter sound?
- Where should diffusors be positioned?
- How do diffusors affect imaging?
- How far away should a listener be positioned?

We will attempt to present some experimental and theoretical observations, however, some explanations involve psychoacoustics research and the audibility of comb-filtering interference, which is beyond the scope of this brief bulletin and the personal research expertise of the authors.

One of the interesting aspects of acoustics, as opposed to other sciences, is the "personal-preference" factor, because sound is interpreted by a bio-computer (ear-brain), that has been programmed by experience as well as scientific input. Therefore, some people like opera and some like rock, some like pin point sharp sonic images and some like sonic images with a more natural width, some like this and some like that. Equally important, is the fact that some bio-computers are defective, yet still capable of expressing an acoustic opinion. This brief description will attempt to focus on the physics of diffusors, since the authors are not fully aware of the operational state of their bio-computers, after too many years of 7/24/52 continuous operation.

INTRODUCTION

Diffusion has certainly been with us since antiquity in the form of statuary, coffered ceilings, relief ornamentation, columns, etc. These surfaces were used, whether knowingly or unknowingly, to create many wonderful performance spaces; and the importance of diffusion in these spaces has been verified by measurements and listening experience. However, these surfaces, though beautiful, can have limited spatial scattering capability and bandwidth. In the early 80's, RPG was founded to begin a research analysis of sound scattering surfaces, both theoretically and experimentally.

The discipline of Architectural Acoustics was founded over 100 years ago by Wallace Sabine. During that time most of the focus was on absorptive surfaces. A significant amount of research has been devoted to absorptive mechanisms and to quantify their performance, standards have been set up to evaluate the random incidence and normal incidence efficiency. Even with all of this effort, we are still dealing with random incidence absorption coefficients that exceed one! By contrast, acoustically designed scattering surfaces are still in their formative years. Over the past 30 years significant progress has been made in the theory, design, prediction, optimization, measurement and characterization of these important surfaces. As Co-Chairmen of the Characterization of Acoustical Materials Working Group, the authors are very proud of the fact that the first information document describing how to characterize the scattering uniformity of a diffusing surface has been published as AES-4id-2001 in J. Audio Eng. Soc., Vol. 49, No. 3 (March 2001). We are also working to establish standards for random incidence scattering coefficients, which are needed in geometrical room modeling programs. This work is taking place with an international working group in ISO WG25.

RPG's exploration into the field of acoustical scattering began with a paper delivered to the AES in the same meeting where the CD was being introduced, almost 20 years ago! ["P. D'Antonio and J. Konnert, "The Reflection Phase Grating Diffusor: Design Theory and Application", J. Audio Eng. Soc. Vol. 32, No. 4 (April 1984)".] The simple quadratic residue diffusors described back then have been significantly improved over the years. In fact, the design paradigm of equal energy in the diffraction directions, proposed by Manfred Schroeder, has been expanded to equal energy in all directions, with the additional capability of providing energy in "desired" directions. While some of these simple number theoretic surfaces are still quite useful, the new state of the art in diffusor design utilizes a new optimization algorithm, which combines the power of the boundary element and multi-dimensional optimization techniques. We will refer to this new software as a Shape Optimizer. The research carried out over the past 20 years has been reviewed in several published papers and a new book called "Acoustic absorbers and diffusers: theory, design and application" by Trevor Cox and Peter D'Antonio will be published later this year by Spon Press. For those interested in further reading, technical publications are referenced at the end of this publication.

The architectural acoustics industry is now close to the stage where it is possible for acousticians to evaluate potential diffusors in the marketplace and to specify their diffusion, as is the common practice with absorption coefficients for absorbing surfaces. From this point of view, the acoustic industry has made significant strides with the challenge of keeping acoustical pace with the incredible advances in the electronics industry.

WHAT IS A DIFFUSOR?

When sound is incident upon a surface, some energy is removed, through absorption or transmission, and some energy is scattered. When the sound is scattered in only one direction, where the angle of incidence equals the angle of reflection, the scattered energy is generally called a specular reflection. When the energy is scattered uniformly in many directions and temporally dispersed, the scattered energy is called a diffuse reflection. In a specular reflection, most of the energy is concentrated into a very short period of time, whereas the energy in a diffuse reflection is distributed over a longer period of time. To understand what a diffusor is, it is helpful to understand why a specular reflection is constrained to only one direction, the specular direction. To understand this it is useful to use a construct introduced by Huygens to explain light scattering.

Huygens Principle:

Huygens proposed a very interesting construct to describe light scattering from a surface, which can be used to understand sound scattering. The idea is to subdivide the scattering surface into a set of secondary point sources, which radiate hemispherically. These secondary sources hemispherically radiate forming concentric wavelets, which interfere to model the reflected sound. Lines are drawn through points on the reflected wave, which are in phase with each

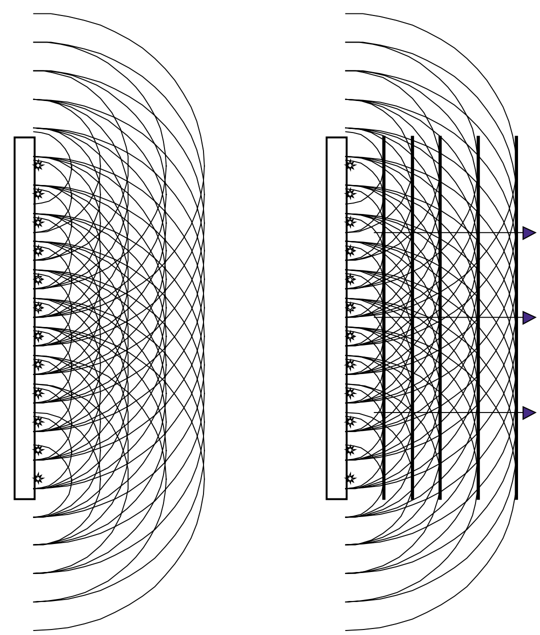

Figure 1. Huygens description of specular scattering

other. These lines are the wavefronts, which show the direction and propagation of the reflected sound. Figure 1 shows the effect of a normally incident plane surface, which produces a reflected plane wave in the specular reflection direction, where the angle of incidence equals the angle of reflection. Phase relationships in other directions, destructively interfere and hence only the specular scattering remains.

How can a flat surface be modified to allow sound to be scattered in other directions than just the specular direction? Since sound can be described by its phase and amplitude, it will be seen that one can modify the directionality of scattered sound by modifying the phase and amplitude of the scattered wavelets. One can modify the phase, by creating a surface topology with depth variation. In this case the surface is called a reflection phase grating (now you know what RPG stands for). If the amplitude is modified by forming reflective and absorptive areas on a surface, you create a reflection/absorption amplitude grating. Both approaches have been used to create a large family of

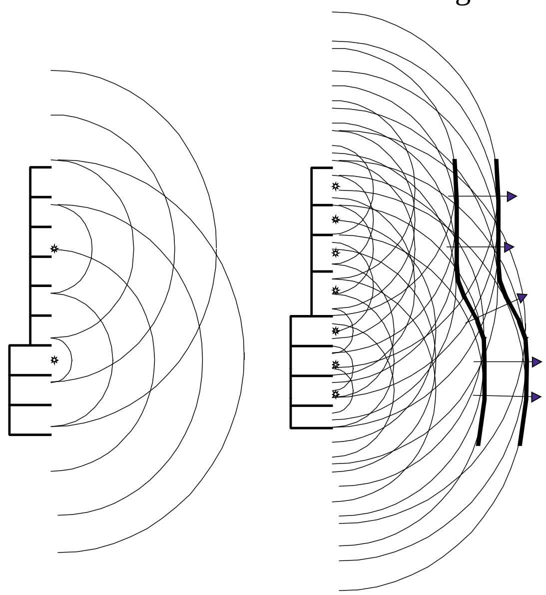

Figure 2. Huygens construct for a reflection phase grating

diffusing surfaces for different applications. In Figure 2, we show how creating a phase grating by introducing a series of wells of equal width but different depth, separated by dividers, can introduce a redirection of the scattered wave. These phase gratings, which were initially described by simple number theory sequences, can now be optimized using the Shape

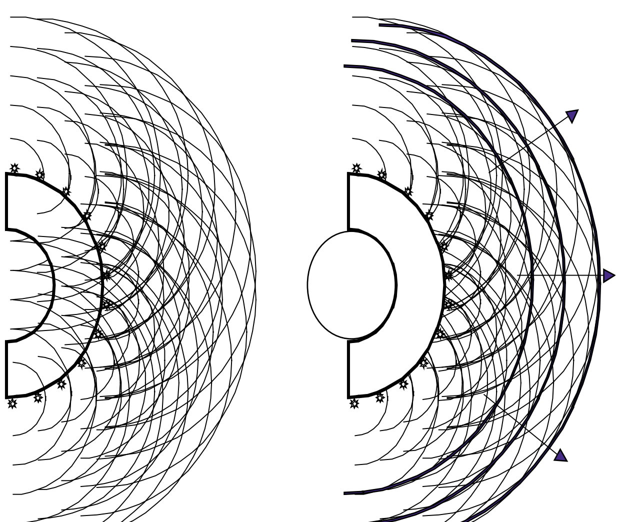

Figure 3. Huygens construct for a curved surface

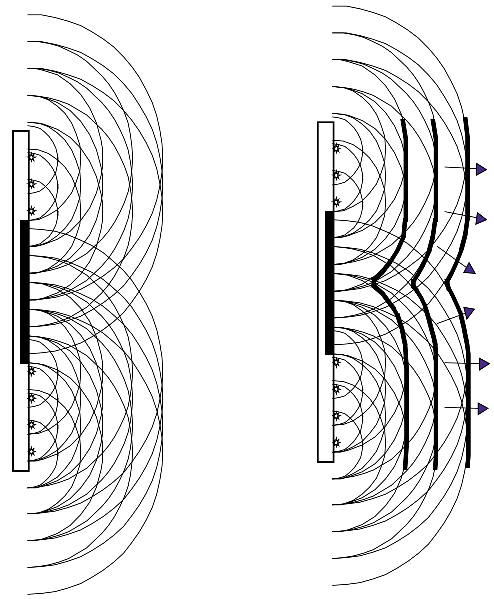

Figure 4. Huygens construction for a hybrid reflection/absorption amplitude grating

Optimizer. One can also provide diffusion using optimized curved surfaces as seen in Figure 3, in the form of a simple semicylinder. In Figure 4, we illustrate how a series of reflective and absorptive areas can also cause a non-specular reorientation of the scattered wave. Notice how the solid ares in the center of the diagram does not contribute any point scatterers, since this energy is absorbed. A diffusor is thus defined as a surface that uniformly scatters incident sound and is invariant to angle of incidence, the angle of observation and the frequency, within its bandwidth. They should also have a temporal signature different from the incident sound, and this is usually done by creating temporal dispersion.

HOW DO DIFFUSORS SCATTER SOUND?

We have mentioned phase gratings, optimized shapes and amplitude gratings as possible types of diffusors. These can be further divided by the nature of their spatial distribution. When the phase or amplitude variation is in only one direction, we call these diffusors one-dimensional or 1D diffusors. An example of the polar distribution is shown in Figure 5 (left). In a 1D diffusor, the sound is scattered into a hemidisk in the direction of the phase or amplitude variation and specularly oriented in the other direction. These 1D diffusors can be thought of as an extruded profile and thus contain reflection phase gratings, optimized extruded curved surfaces, extruded fractals, columns,

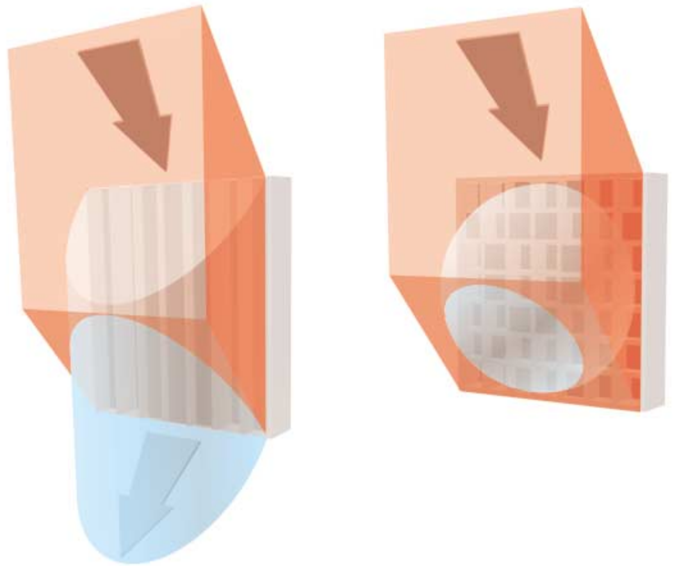

Figure 5. Left- polar response for a 1D diffusor; Right- polar response for a 2D diffusor

amplitude gratings. A 2D diffusor uniformly scatters sound into a hemisphere, independent of the angle of incidence. Because the 2D diffusor scatters sound omnidirectionally, the energy in a comparable direction for a 2D diffusor is half of what it is for a 1D diffusor. 2D diffusors include optimized divided and non-divided phase gratings, new optimized contoured surfaces and amplitude gratings.

Using the Boundary Element Technique we can calculate and visualize how sound is scattered from surfaces. To illustrate this, Figure 6 shows the 3D specular polar scattering from a flat reflecting surface with parallel wood battens, a redirecting surface in the form of a square based pyramid, and an optimized 2D phase grating diffusor. The polar responses are calculated for normal incidence at 2 kHz. The specular reflection is very directed with small lobing due to the wood battens. The redirected specular reflections from the square based pyramid follow the symmetry of the four triangular faces. The 2D diffusor uniformly distributes the scattered sound into a hemisphere.

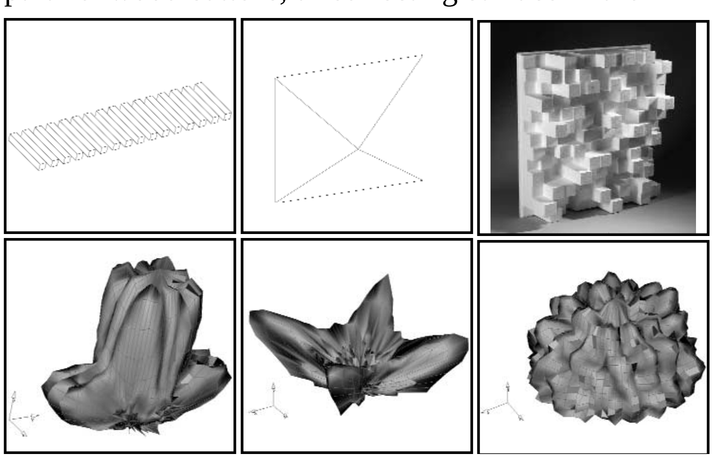

Figure 6. Polar responses for normal incidence at 2 kHz for a flat surface with battens, a square based pyramid and an optimized 2D phase grating

WHERE SHOULD DIFFUSORS BE POSITIONED?

In a critical listening room, the boundary surfaces are usually rather close to the listener. The most efficient placement for a diffusive surface or an absorptive surface, is at the first bounce specular position. Consider a room in which all of the surfaces are mirrored. These positions would be at all of those positions on the boundary surfaces at which a listener can see the source. The consequence of placing diffusors at these positions is reflected in the effect they have on imaging and coloration.

HOW DOES A DIFFUSOR AFFECT IMAGING?

It is often useful to consider the extremes or boundary conditions when attempting to solve a problem. In the case of a critical listening room, we have one extreme of a completely anechoic room, an anechoic chamber, and the other of a completely reverberant room, a reverberation chamber. Anyone who has spent any time in these rooms realizes that neither is an exciting place to listen to music. In the early 80's, there was an interest in improving the design of stereo listening rooms. Since there was psychoacoustic and measurable evidence that early reflections affect the characteristics of the sound at the listening position, absorption was used to control reflections between the source and the listener to provide what we have called a temporal and spatial reflection free zone (RFZ). It was temporal, because the interfering reflections were controlled only during a certain time window, until reflections from the rest of the room arrived; and spatial, because the reflection free zone only existed within a certain area in the room. Following this temporal RFZ, reflections from the rest of room would arrive and be audible. Since the desire was not to have strong specular reflections from the rear wall as these affect what is heard, and there was a desire not to make the rear of the room absorptive, leading to a dead room, diffusion was explored as an alternative way of introducing the energy following the reflection free zone. These rear diffusors essentially provided a "passive" surround sound, that was intended to provide ambiance in the room and minimally interfere with the direct sound.

How much diffusion should one use? This depends on what a listener's personal preference is. If these rear reflections, or any other first-order reflections in the room, are absorbed, then one experiences the highest resolution of sonic images- essentially points in space. If diffusion is used to control any of these reflections, the apparent size of the image is broadened. If done properly, some have described this as a more natural size image, similar to what might be experience in the presence of an actual sound source.

So a balance has to be achieved in which the desired apparent source width and depth is achieved, while creating the desired ambiance. While some people favor very dead spaces for mixing audio, others do not. Many of the industry's leading mastering facilities are using rooms with a combination of absorption and diffusion. Consequently, if some liveliness is to be left in the room, a combination of absorption and diffusion is better than absorption and reflection.

As stereo has given way to the various surround formats, we no longer rely completely on phantom center images, since we have center channels. "Passive" acoustic surround can now be used to complement the "active" surround channels, by creating the desired combination of image size and ambiance.

HOW FAR AWAY SHOULD A LISTENER BE POSITIONED?

This question can be answered by considering the concept of a working distance. The working distance is the optimal distance a listener should be positioned from a scattering surface. The distance can be determined by considering the scattered or total field.

Scattered Field

The question is how much distance does the device need to create a coherent wavefront. Essentially, is the listener in the near field or far field. There is an analogy to loudspeakers here. One would not consider sitting 12" from a multi-way loudspeaker, because the listener would be in the near field of one of the band passed speakers. At some distance from the speaker, all individual high frequency, mid frequency and low frequency speakers will combine to form a coherent wavefront. The same holds true for scattering surfaces. They also can be thought of in terms of near and far field, although the situation is a bit more complex than for loudspeakers.

The scattered field can be described by the temporal, spatial and frequency response. The time response describes the level of scattered sound versus the arrival time from a source at a given angle of incidence and a given angle of observation, with respect to the surface normal. For a flat, loss-less reflecting surface of infinite size, the time response is a replica of the direct sound, oriented in a specular direction. For a finite sized panel this consists of a specular arrival and boundary effects. An example of a finite size panel is shown at the top of Figure 7A and 7B. The frequency response describes the level of scattered sound versus frequency, from a source at a given angle of incidence and a given angle of observation, with respect to the surface normal. For a surface of finite size, the frequency response is typically a high pass filter with a low frequency cutoff and ripple determined by the size of the panel.

The temporal and frequency response for a diffusor is shown in Figure 7C and 7D. Note the scattered energy from the diffusor is dispersed in time and the frequency response is characterized by a series of irregularly spaced frequency notches and peaks, typical of what would be measured in a room having a diffuse field.

The temporal and spatial response for an absorber, which attenuates incident sound, a reflector, which redirects incident sound and a diffusor, which uni-

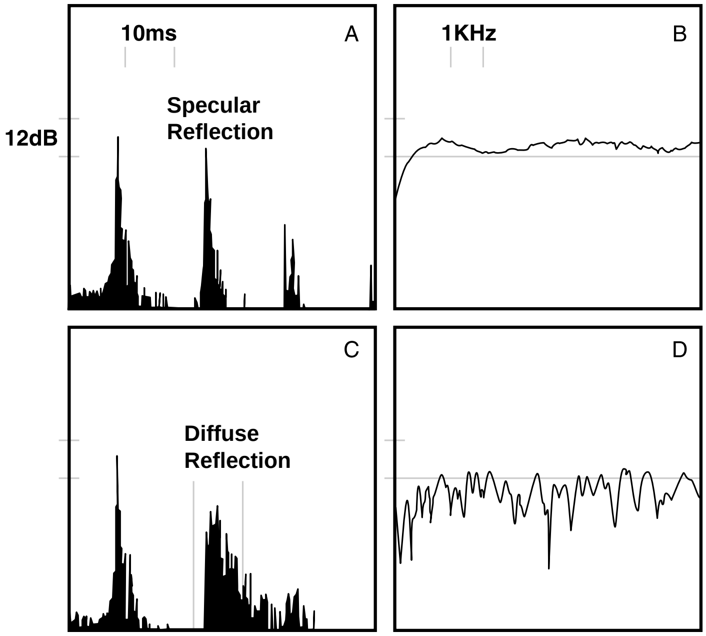

Figure 7 . Time and frequency responses (A and B) for an isolated specular reflection and an isolated diffuse reflection (C and D). The time window used in the Fourier transform to generate the frequency response is indicated by the two vertical lines in (C).

formly disperses incident sound is shown in Figure 8.

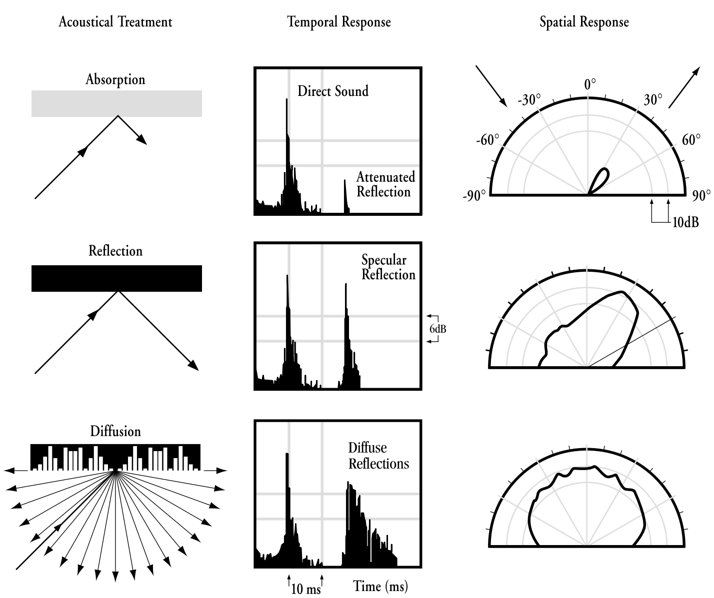

Figure 8. Temporal and spatial responses for an absorptive surface, which attenuates incident sound, a reflective surface, which redirects incident sound and a diffusive surface, which uniformly distributes incident sound.

Near field- far field

One can also describe the scattered field by its spatial response. This is similar to the far field polar response of a loudspeaker, however, the polar response of a diffusor is much more difficult to measure in the far field and this has been the subject of extensive research and AES-4id-2001 standards activity. In the far field, the polar response of an ideal diffusor is invariant to the angle of incidence, the angle of observation and the frequency, within its operational bandwidth. To be in the far field of a scattering surface there are two criteria to satisfy: the observer distance should be large compared to wavelength and the differences between path lengths from points on the surface to the observer should be small compared to wavelength. With the geometries and frequencies used for acoustic diffuser scattering, it is the latter criterion that is most exacting. Unfortunately, in most critical listening room applications, it is usual for sources and receivers to be in the near rather than the far field, so that listeners should be positioned as far from scattering surfaces as possible. It is suggested that a listener should be at least three wavelengths away from scattering surfaces. Since diffusors used in listening room applications have a lower frequency limit of roughly 300-500 Hz, this would mean a working distance of 10’ (3 m) or larger is recommended.

Just as one would not listen to a 3 way loudspeaker with their ear close to the midrange driver, one should expect sonic anomalies when seated too close to a diffusing surface. Many of the phasing anomalies reported by room designers are simply due to the fact that they are not far enough away from the diffusor and they are hearing near field comb filtering and lobing effects. Furthermore, getting too close to a diffusor means that the reflections are dominated by the surface close to the ear, which means the temporal dispersion generated by the diffusor is not heard. The direct and reflected sound are then rather similar and interference gets worse. This naturally leads us to a consideration of the total field.

Total Field

So far we have considered only the scattered sound from a diffusor. When we listen to music in a room, we are listening to the total field, the direct sound and the scattered sound. If the scattered sound predominates, we hear an aberration. Just as room reflections affect the size and directionality of sonic images, they also can introduce coloration, usually defined as a distortion of the spectral content or timbre of the direct sound. Studying the total field offers some insight into why scattering surfaces may introduce coloration.

Earlier we illustrated the time and frequency response of isolated specular and diffuse reflections, now let's consider the time and frequency response of the total field. Consider the effects when a listener is approximately 1 m from the scattering surface. When the scattered sound is derived from a flat surface, the reflected sound and direct sound are relatively comparable in level and the result is a comb filter (Figure 9 top). Not very representative of the content of the direct sound. While this looks rather bad, comb filtering may not be perceived due to the relationship between the frequency of the nulls/peaks and auditory critical bands and the masking by other reflections. When the scattering surface is a diffusor, the scattered

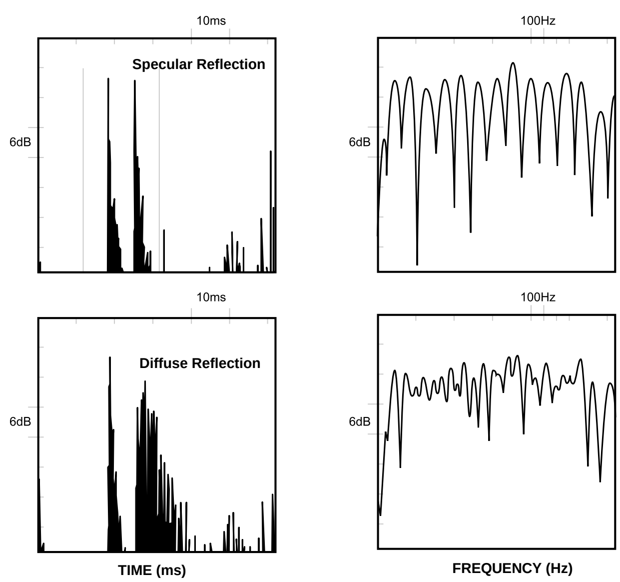

Figure 9. Time (left) and frequency response (right) for the total field consisting of the direct sound and a specular reflection (top) and the direct sound and a diffuse reflection (bottom)

time response is dispersed in time, the spatial response is more uniform and the frequency response consists of an irregular spacing of null and peaks as in a diffuse sound field. The frequency response of the total field more closely resembles the direct sound, since diffusion has minimized the interference. Importantly, the listener no longer picks up the regularity of the nulls and maxima that were seen for the flat surface in Figure 9, and so the spectral changes introduced may be less noticeable. This is illustrated in the bottom time and frequency response of Figure 9, for a 1D diffusor. 2D diffusors, which direct more energy away from the listener, will further reduce the level of scattered energy in the direction of the listener. Recent research has now led to hybrid reflective/absorptive surfaces, which consist of reflective and absorptive areas. These diffusors provide both absorption and diffusion and may allow the listener to get even closer to the scattering surface.

The level of the scattered sound and the resulting interference in the total field decreases in the following order: flat surface, curved surface, 1D phase grating, 2D phase grating, 1D amplitude grating, 2D amplitude grating, absorber. In light of these remarks, it is important to consider the temporal, spatial and spectral response of a sound diffusing surface. Casual forays into arbitrary shaping of surfaces is discouraged and designers should solicit theoretical or experimental proof of performance characteristics from vendors.

TIME DOMAIN EXAMPLE

Let's look at a critical listening room measurement before and after both absorptive and diffusive treatment in Figure 10. At the top we see the time response before treatment, where all surfaces were completely reflective. The measurement microphone is at the listening position. Hence before treatment one can see the interfering side wall and floor reflections, the ceiling reflection and a series of sparse room reflections. The wall, floor and ceiling reflections were treated with broad bandwidth absorption to create a reflection free zone and the rear wall was treated with diffusion to create a spatially and temporally dense reflection pattern characteristic of a diffuse sound field.

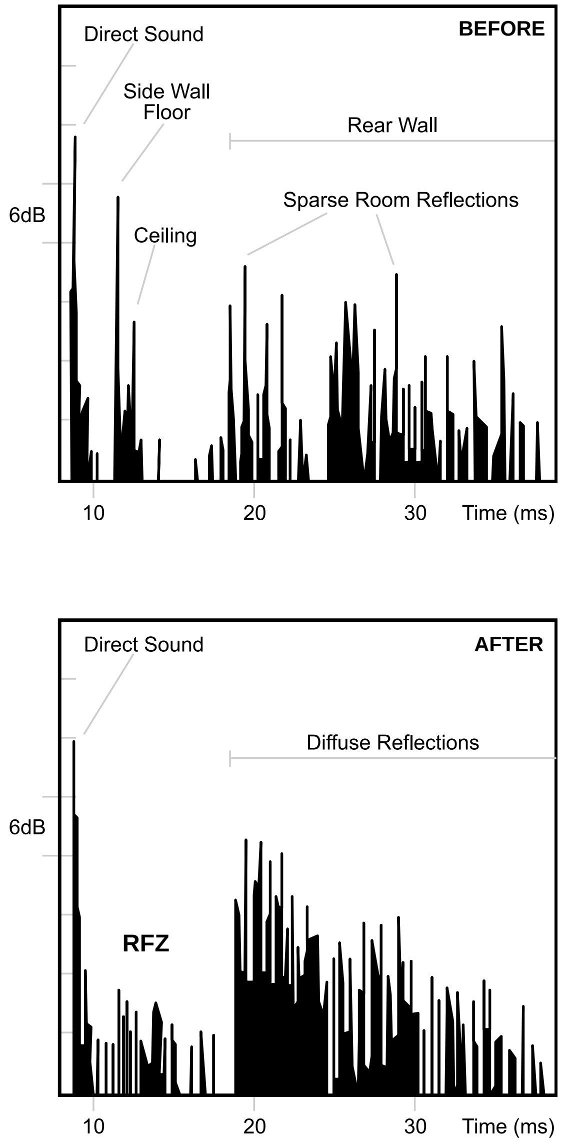

Figure 10. Before and after acoustic treatment time response of a critical listening room.

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Some abstracts from this research can be found at http://www.rpginc.com/research/index.htm

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