In this presentation we will discuss the acoustical design of rooms in which good speech intelligibility is required. These include rooms used for teaching, meetings, conference, distance learning, lectures and presentations. To properly design these rooms we must provide isolation from external and internal noise interference and control of interfering reflections and reverberation, i.e. we must provide noise control and sound control. Noise interference sources will be identified and materials for mitigating them will be presented. Absorptive, reflective and diffusive sound control surface treatments will be described. Then utilizing noise and sound control elements, we will discuss the acoustical design of a range of spaces in which high speech intelligibility is required.

**NOISE CONTROL**

Noise interference can arise from airborne and or structural borne noise. Any vibrating source can modulate the air and create airborne sound. Airborne sound can infiltrate a speech room via transmission through partitions and through any common path with adjacent rooms. These common paths are referred to as flanking paths, in that even if room boundaries were sufficiently isolated, airborne sound can still flank or bypass the room boundaries rendering them ineffective. Flanking can occur through common HVAC ducts or common floors and ceilings. Travel through common HVAC ducts is understandable, but airborne sounds can cause the common ceiling or floor to vibrate and transmit the sound to an adjacent room and re-radiate. Impulsive sounds caused by footfalls or any direct excitation of a common surface can also flank room boundaries. These paths are shown in Figure 1.

![Figure 1. Illustration shows airborne noise paths through a common wall and flanking paths through a common floor, ceiling and HVAC duct.](image)

As an example, it is common to see two offices separated by a common wall, with a common transmitted sound (≈9%) and transmitted sound (≈10%).

![Figure 2. Illustration dispels the common myth that placing porous absorption on a barrier wall will decrease the transmitted sound.](image)
ceiling and floor. It should be appreciated that despite how effective the common wall and doors may be, the room is destined to be compromised by flanking through the common floor, diffraction over the common wall through the typical ACT ceiling and via the common HVAC ducts. The only way to improve this design is to provide a separate floor and ceiling in each room, breaking the flanking path and addressing the common HVAC duct. There are two factors that contribute to noise control and they are mass and isolation. There is a common myth associated with isolation, which states that placing absorption on a room boundary will decrease the transmitted sound. Figure 2 shows that the use of a standard fabric wrapped absorptive panel on a room boundary only affects the acoustics within the room, but does little to control transmission through a partition. Improved transmission loss is achieved by increasing the mass, providing an air gap and isolating the partition using a resilient material. Isolators can be either springs, which are effective below 5 Hz, or a wide range of elastomers including, natural rubber, polyurethane, cork-rubbers, recycled tires and microcellular foams, which are effective above 5 Hz. The theory of isolation is very mature. It states that the effectiveness of the isolation depends on the ratio of the disturbing frequency, \( f_d \), and the natural frequency of the isolator, \( f_r \). It can be seen in Figure 3, that when the ratio, \( \beta \), of the disturbing frequency and the natural frequency of the isolator is equal to one, amplification occurs, making the sound louder. At a ratio of the square root of 2 (1.41), the Transmissibility (the sound that is transmitted through a partition) is equal to 1, meaning all of the sound passes through the partition. As this ratio increases we enter an isolation region in which the transmissibility drops rapidly as the ratio increases. In Figure 3, we also show a chart of Isolation Efficiency, also called Transmission Loss, in which it is shown that to provide isolation of airborne and structurally borne sound, we must use an isolator with a resonant frequency lower than the disturbing frequency of the noise. The lower the resonant frequency of the isolator compared to the frequency of the noise the greater the isolation. Typical values of \( \beta \) would be greater than 1.41. For example, to isolate a noise source of 60 Hz, and isolator with a resonant frequency of 15 Hz, common for a natural rubber or polyurethane, would provide 95% isolation. In the lower part of Figure 3, we show how the transmitted sound is progressively decreased by increasing the mass of the partition, introducing an air cavity using a resilient material and lastly floating the partition on a resilient material, separating it from the structure.

There are well established materials to isolate floors, walls and ceilings and some examples are shown in Figure 4. Floors are easily isolated by floating a floor consisting of a lamination of plywood/gypcrete/plywood on polyurethane elastomers spaced in a roll-out polyester mat. When there are height restrictions, a wavy recycled rubber mat can be used, with a compromise in isolation efficiency. The most cost effective way to design a room is to isolate the floor as described and rest the walls on the floor and the
ceiling on the walls. Resilient material is used to separate the walls from the floor and ceiling from the walls. To properly account for the added weight of the walls and ceiling a separate strip of isolators is effective around the perimeter of the room. When this design is not appropriate, walls can be isolated with drywall isolation clips and the ceiling can be suspended with spring or elastomer isolators from the structure.

SOUND CONTROL

Once the room is isolated from external noise interference, the next concern is internal room acoustics. This is typically determined by acoustical treatment on the walls and ceiling. The sound that we hear in a room is determined by the direct sound and indirect reflections from the room’s boundaries and internal contents. Control of reflections using absorption has been in practice for over a hundred years, since Sabin linked reverberation with the absorption coefficient. In fact, the term acoustical surface has almost become synonymous with an absorbing surface. The fact is that there are three acoustical surfaces, namely absorptive, reflective and diffusive, as shown in Figure 5. An absorptive surface attenuates sound, a reflective surface redirects sound and a diffusive surface uniformly scatters sound. Since absorptive surfaces have been available and are relatively affordable, they tend to dominate acoustical design of office spaces. This presentation is intended to describe how we can improve on using solely absorptive surfaces. To do so we will describe the current absorptive and diffusive surfaces, how to measure and characterize them and where and how to use each. Keep in mind that an effective acoustical design is achieved only through an appropriate combination of absorptive, reflective and diffusive surfaces.

Absorption

Let’s begin by describing the three types of absorptive surfaces, namely porous, resonant and diaphragmatic, shown in Figure 6. The most common are the porous absorber, typically acoustical ceiling tile (ACT) and fabric wrapped fiberglass, rockwool, polyester or cotton panels. These surfaces absorb sound by converting sound energy into heat, due to friction in the interstitial voids in the material. A second mechanism involves resonance of a small air mass in a hole or slot against a larger volume of air behind it acting like a spring. To extract energy and broaden the bandwidth, a porous material is placed in the cavity close to the opening, where the particle velocity is a maximum. Products employing this absorption mechanism include perforated or slotted wood panels and slotted concrete masonry units. The last option is a membrane absorber consisting of a vibrating limp mass that moves air through a porous absorber or a damped rigid metal plate. The important thing to appreciate about each of these absorbers is that they each have a limited frequency range in which they provide effective absorption, as shown in Figure 7. Porous absorbers in the form of fabric wrapped panels, typically used in offices, absorb preferentially in the high-mid frequencies, depending on thickness and mounting. If used
solely and in excess can cause more harm than
good, by overly deadening the room. It is impor-
tant to examine the absorption efficiency versus
frequency and not just the NRC or Rw. For exam-
ple, two treatments can have the same NRC, but
very different absorption spectra. In Figure 8, we
compare a fabric wrapped panel and a perforated
wooden panel. They both have the same NRC;
however, the perforated wooden panel provides
more uniform absorption in the mid and low fre-
quencies, which often is desirable. Since the fab-
ric wrapped panel is an attractive option, we have
developed an approach to improve it, using a vari-
able impedance surface, consisting of absorptive
and reflective areas. The binary amplitude diffus-
ing absorber (diffsorber) consists of a specially
designed perforated template on the face of a
porous absorber. The location of the perforations
is specified by an optimal two-dimensional mathe-
matical binary sequence, where a hole is placed
when the sequence value is zero. The template
accomplishes two things. It uniformly scatters the
high frequencies, instead of absorbing them and
deadening the room, and it diaphragmatically in-
creases the mid-low frequency absorption, which
is desirable. The design can be seen in Figure 9.
At the top left the two dimensional sequence of

\[
\text{NRC} = \frac{0.24 + 0.69 + 1.05 + 1.10}{4} = 0.80
\]

Both have the same NRC, but the perforated panel option offers more
desirable low and mid frequency absorption.

Figure 8. The fabric wrapped panel and the per-
forated wood absorber have similar NRC values,
but the perforated wood panel is more effective in
the mid and low frequencies.

Figure 9. Top left: Binary amplitude diffsorber
(BAD) template; Top Right: Fabric covered and
exposed BAD panels; Bottom left: 1”, 2”, 3” and 4”
fabric wrapped fiberglass absorption coefficients;
Bottom middle: absorption coefficients for 1”, 2”,
3” and 4” BAD panels compared to 1” fiberglass
(dotted); Bottom right: cutaway view of fabric
wrapped BAD panel.
holes forming the binary amplitude grating is shown, also indicating that the holes are places where the sequence has a zero value. In the upper right, various embodiments of the BAD panel are shown, including flat and curved fabric wrapped panels, exposed flat and curved metal and exposed wood with and without back lighting. In the lower left we see the absorption coefficients for conventional fabric wrapped panels of 1”, 2”, 3” and 4” thickness. As the thickness increases the low frequency absorption also increases. In the bottom middle graph, we show how the BAD panel decreases the high frequency absorption and increases the mid and low frequency absorption as a function of the same four panel thicknesses. We also show the absorption spectrum for 1” fiberglass for comparison. In the bottom right a cutaway view of a fabric wrapped BAD panel is shown. The BAD panel is a useful evolution of the conventional fabric wrapped panel for office use.

In addition to fabric wrapped absorbers, BAD panels and macro and micro perforated wood, one can also use a new class of transparent microperf and microslit absorbers. Microperf and microslit designs absorb sound through viscous losses in the less than 0.2 mm diameter holes, which are comparable to the thickness of the boundary layer of air. These are especially useful when daylight and natural views are desired. The microperf option is available in 100 micron microperf polycarbonate or fire-rated ETFE foils, Figure 10, or acrylic or PETG panels, Figure 11 right. The microslit option, Figure 11 left, is available in panel form from 2 - 5 mm thick. The microslit panels can be digitally printed for graphics or signage, as seen in Figure 12.

**Figure 10.** Microperforated foil and absorption coefficients.

**Figure 11.** Microslit and microperf panels and their absorption.

**Figure 12.** Top left: transparent foil window treatment; Top right: translucent foil radiant ceiling treatment; Bottom left: transparent microslit panel window treatment; Bottom right: transparent microslit panel window treatment; Center: digitally printed microslit panel.

**Diffusion**

Diffusion is a process by which incident sound energy is uniformly scattered, Figure 13. The earliest forms of diffusion consisted of classic architectural columns, statuary, relief ornamentation, etc., Figure 14. As these classic forms disappeared from common use, geometrical forms were used to provide scattering. While providing useful scattering and classic beauty, the diffusion performance was not predictable and the band-
width limited. In the early 1980s, RPG introduced the first reflection phase grating diffusors, based on mathematical number theory. These were the first diffusing surfaces that could be designed with predictable performance and scattered sound uniformly over a broad range of frequencies. These periodic surfaces consisted of either divided wells or raised blocks, whose relative depths or heights were specified by a mathematical sequence, like the quadratic or primitive root sequence, which insured that the sound was scattered uniformly in the diffraction directions, which is determined by the size of the repeat unit. Over the next 30 years, these gratings were optimized. As architecture moved from rectilinear to curvilinear forms, RPG created a shape optimization software to reverse engineer the surfaces to go from a design motif to optimized scattering performance. All of these surfaces are shown in Figure 14.

One might ask “why do we need diffusion”? The answer is illustrated in Figure 15. We are all familiar with air diffusers which provide uniform temperature and prevent cold and hot zones. We are all familiar with lighting diffusers which uniformly illuminate a room removing optical glare and minimizing light and dark zones. Similarly, a sound diffusor uniformly distributes sound in a room, to provide ambiance, even coverage and removes acoustical glare caused by strong specular reflections. As we have seen, the sound con-

Figure 13. A ideal diffusor uniformly scatters incident sound from any angle of incidence over a broad range of frequencies.

Figure 14. Diffusor surfaces including, top: early classic architecture forms; next: geometrical forms; next: number theoretic reflection phase gratings and bottom: 1D and 2D shape optimized forms and the BAD panel.

Figure 15. Air diffusers provide uniform temperature and prevent cold and hot zones.

- Lighting diffusers to uniformly distribute light in a room and remove optical glare and minimize hot spots and dark zones
- Similarly, Sound diffusors uniformly distribute sound in a room, to provide ambiance, even coverage and remove acoustical glare, caused by strong specular reflections

Figure 15. Air diffusers provide uniform temperature, lighting diffusers provide uniform illumination and sound diffusors provide uniform sound coverage and ambiance.
The control acoustical palette consists of absorption, reflection, and diffusion. While the design of spaces used for speech have relied solely on absorption, it should be appreciated that an optimal design can only be achieved using an appropriate combination of each ingredient.

Sound absorption is measured in a reverberation chamber, according to ISO 354. Sound diffusion is measured in either an anechoic chamber or in a reflection free zone on the floor of a reverberant space, according to ISO 17497-2. Figure 16 shows the complex process necessary to determine the diffusion coefficient. In the center of Figure 16, we show a boundary method goniometer with the sample at the center of a 1 m semicircle containing 37 measurement microphones and a 2 m concentric circle containing the loudspeaker providing the test signal; Left: Data reduction process for a reference reflector; Right: Data reduction process for a diffusor. Note the diffusor exhibits a uniform polar response, whereas the reference reflector scatters the sound in a specular manner, like light from a mirror.

Figure 16. Center: 1D boundary method goniometer with the sample at the center of a 1 m semicircle containing 37 measurement microphones and a 2 m concentric circle containing the loudspeaker providing the test signal; Left: Data reduction process for a reference reflector; Right: Data reduction process for a diffusor. Note the diffusor exhibits a uniform polar response, whereas the reference reflector scatters the sound in a specular manner, like light from a mirror.

Figure 17. Top row left to right: 2D Omniffusor and Skyline layin T-bar ceiling treatment; 2D Harmonics T-bar layin ceiling treatment; Oriented 1D Modffusor wall treatment. Bottom row left to right: 2D Bicubic ceiling clouds; Stretch fabric covered 2D BAD panels; Exposed wooden furniture grade BAD panels.
plane goniometer with the sample at the center of a 1 m semicircle containing 37 mics every 5 degrees and a 2 m concentric circle containing the loudspeaker delivering the test stimulus. The sample is irradiated with a test signal at angles of incidence of 30, 60, 90, 120 and 150 degrees, and the impulse response at each observation angle is measured. In the left panel we show the measurement and data reduction for a reference reflector at an angle of incidence of 150 degrees (A). The impulse response of the scattered sound, at each observation angle, is isolated (B and C) and transformed into the frequency domain (D). Then third octave polar responses are calculated and the diffusion coefficient is determined (E) from the uniformity of the polar responses and normalized by the diffusion coefficient of the reference reflector. In the upper right hand corner, we show colored narrow band polar responses, from which the third octave band responses are derived. The right panel illustrates the same data reduction process for a diffusor. Note that the polar responses of the diffusor are close to being semicircles with uniform scattering, whereas the reflector exhibits specular behavior, wherein the scattered sound is directed at an equal and opposite angle to the incident direction.

Diffusion can complement absorption and reflection with application on walls and ceilings as shown in a few installations in Figure 17, utilizing omnidirectional (2D) scatterers, in the form of Omniffusor, Skyline, Harmonics and Bicubic diffusors, as well as single plane (1D) Modffusors, oriented vertically and horizontally.

ROOM DESIGN

Let us now apply the noise and sound control acoustic tools to the design of training rooms, conference and meeting rooms and lecture halls and presentation rooms, where high speech intelligibility is required, using the complete acoustical palette, instead of just absorption. What did you say? Can you hear me now? A good acoustical design mitigates the need for these questions.

The ear/brain processor can fill in a substantial amount of missing information in music, but requires more detailed information for understanding speech. The speech power is delivered in the vowels (a, e, i, o, u and sometimes y) which are predominantly in the frequency range of 250Hz to 500Hz. The speech intelligibility is delivered in the consonants (b, c, d, f, g, h, j, k, l, m, n, p, q, r, s, t, v, w), which requires information in the 2,000Hz to 4,000 Hz frequency range. People who suffer from noise induced hearing loss typically have a 4,000 Hz notch, which causes severe degradation of speech intelligibility.

**Why would we want to absorb these important frequencies on the ceilings of speech rooms and prevent them from fusing with the direct sound, thereby making it louder and more intelligible?**

Research has revealed the importance of early reflections and reverberation to intelligibility. There is a difference in hearing speech and understanding it. When early reflections arrive between in a temporal window roughly 20 - 50 ms after the direct sound and roughly between 5 and 15 dB below the level of the direct sound, there is a process called temporal fusion in which the direct sound is fused with the early reflections making it louder and more
intelligible. This is shown in Figure 18. So one of the central design criteria for small rooms used for speech is to provide early reflections and not absorb them!

Many of the problems that arise in poorly designed speech rooms stem from a low Signal to Noise Ratio. The Signal consists of the Direct Sound & Early Reflections (up to roughly 20 ms). The Noise consists of reverberation, occupant noise, exterior noise intrusion & noisy MEP systems. Adults typically require 0 dB signal-to-noise ratios for high speech intelligibility when listening to simple and familiar speech material for short periods of time. An additional 2 dB is needed to compensate for neurological immaturity. An additional 5 dB is required to compensate for sensorineural and conductive hearing losses. An additional 5 dB is required for limited English proficiency and language disorders. An additional 3 dB is required to compensate for the effects of excessive reverberation. These additional requirements for speech rooms total 15 dB over that of normal adults, or a signal-to-noise ratio of +15 dB. We can use the passive acoustics of the architecture to provide some of this needed gain. Most design approaches only try to reduce the Noise and often simultaneously decrease the strength of the Signal as well, by using only absorption. The result is no net improvement. In Figure 19, we see the corrupting effect of reverberation noise on the purity of the speech signal. At the top in red, we see the anechoic speech signal waveform. Below that we see how the speech signal is progressively degraded with reverberation (green) in rooms with reverberation times of 0.8 sec, 1.3 sec and 2 sec.

The best approach is to decrease the Noise and simultaneously increase the Signal by providing:
- reflective areas surrounding the source to increase the apparent level
- absorptive areas around the perimeter of the ceiling to control the decay time
- useful, early, diffuse reflections from the center of the ceiling
- the combination of high frequency diffusing and mid frequency absorbing (diffsorbing) panels on the mid-third of the side and rear walls
- treatment to all surfaces minimizing absorption on the ceiling and floor and reflection on the wall
- isolation of the room from all internal and external sources of noise and HVAC

Figure 20, illustrates the beneficial use of diffusion on the ceiling of speech rooms. Absorption removes these beneficial reflections, reflection redirects them, but only diffusion can uniformly distribute them providing better coverage, cross-communication between participants, and improv-
ing intelligibility. In Figure 21, we compare the Sound Pressure Level and direction of arriving reflections at listeners with an acoustical ceiling tile and a diffusive ceiling. In Figure 21 top left, we see an SPL map at 2 kHz from a source at the center left of the room in two seating areas of the room in a 20 - 50 ms time window. The average level is roughly 68 dB. In Figure 21 top right we show the direction of arriving reflections in a 0 - 50 ms window in the horizontal plane, in the medial plane bisecting the ears and in the frontal vertical plane including the two ears. In Figure 21 bottom left and right, we show the same SPL and reflection directionality when the ceiling is treated with a sound diffusor, as opposed to a sound absorber. It can be seen that the SPL level increases by nearly 6 dB and the sparse reflection pattern with the sound absorbing ceiling is now much more uniform and dense.

Before we provide a concept design, it is important to note that any acoustical treatment used

should be uniformly distributed in the room. In many speech rooms absorption is typically the only treatment used and it is often concentrated on the ceiling and floor, with high frequency absorbing material like acoustical ceiling tile and carpeting. We call this the Single Plane Absorption Syndrome (SPAS). All of the absorption is concentrated in the vertical plane, which actually accentuates the potential flutter reflections in the horizontal plane which is purely reflective. This can be seen in Figure 22, in which a vertical sound ray is attenuated by almost 30 dB due to absorption, while a horizontal sound ray is hardly attenuated at all. This leads to a non-mixing sound field characterized by different reverberation times in the two planes and makes echoes and flutter more audible and problematic. This should be avoided.

Figure 21. Top left: SPL in a room with an acoustical tile ceiling at 2 kHz between 20 and 50 ms; Top right: Arriving reflections at a listener in the horizontal and frontal and medial vertical planes. Bottom left: SPL in a room with a diffusive ceiling at 2 kHz between 20 and 50 ms; Bottom right: Arriving reflections at a listener in the horizontal and frontal and medial vertical planes. Red indicates higher SPL.

Figure 22. Single Plane Absorptive Syndrome. Sound in the vertical plane is attenuated by almost 30 dB from an absorptive ceiling, but hardly at all in the horizontal plane from reflective walls.

Figure 23. Two typical rooms separated by a partition, but including common floor and ceiling.
In Figure 23, we show two typical office rooms separated by a partition. This design suffers from flanking paths from one side to the other through the common floor and ceiling. If high isolation and speech privacy is required, these rooms need a separate floor and ceiling, with the floors separated from the structure on resilient isolators.

In Figure 24, we present a concept design for a speech room consisting of a reflective front wall and ceiling above the presenter to amplify sound, even when the presenter turns away from the audience, absorptive ceiling perimeter and upper third of side and rear walls to control the decay time, diffusive ceiling over the center of the room, diffusorptive surfaces on the mid third of the side and rear walls and reflective lower third of the side and rear walls. Now let's look at how typical designs can be improved.

The first shown in Figure 25, is a classic example of a SPAS design, in which high frequency absorption is provided by ACT on the ceiling and carpeting on the floor. The solution consists of placing diffusorptive on the mid-third of the wall area, shown in yellow, and adding 2D diffusion in the ceiling over the conference table, while maintaining the ACT around the perimeter.

In Figure 26, we show a typical conference room with ACT ceiling, hard reflective soffits, fiberglass panels on side walls and carpeting; essentially all high frequency absorption making the room acoustically “dead”. There is little chance that the speaker can be heard in the rear of the room due to this. This room can be improved by replacing the purely absorptive fabric wrapped panels on the side walls with diffusorptive panels in the areas outlined in yellow. Replace the center of the ACT ceiling with 2D diffusion in the area outlined in red, leaving the perimeter ACT in place.

In Figure 27, we show a typical presentation room with a SPAS design of ACT on the ceiling and carpeting on the floor with reflective walls. This leads to poor propagation of sound to the rear of the room.
Figure 27. Typical SPAS presentation room, with ACT ceiling and carpeted floor. Suggested reflective, diffusorptive and diffusive treatment areas are outlined in blue, yellow and red.

CONCLUSION

We have identified that good acoustical design of speech rooms requires noise and sound control. Noise control involves isolation of external and internal noise sources, providing sufficiently massive and resiliently mounted room boundaries, isolation of all MEP systems, removal of flanking paths from a common floor, ceiling and HVAC ducts. Noise control products were presented and described. Sound control involves creation of a good acoustical environment providing a high signal to noise ratio. The signal is increased by providing reflective areas around the speaker on the front wall and ceiling directly overhead. The signal is further increased by providing early diffuse reflections, using 2D sound diffusors, on the central ceiling area and diffusorptive panels on the mid-third of the side and rear walls. The reverberation is decreased using absorption around the perimeter ceiling of the room and upper third of the side and rear walls. Absorptive and diffusive products were presented and described. In summary, speech rooms with high intelligibility can be created using all ingredients of the acoustical palette, namely, absorption, reflection, diffusion and isolation.