Acoustics and Sound Systems in Architectural Design

By RICK KAMLET

T he need for intelligible speech or pleasant, undistorted music is fundamental to the design of auditoriums, performing arts centers, theaters, concert halls, sports arenas, lecture halls, and churches.

Because good sound is central to the function of so many facilities, it is essential that architects consider the acoustical properties of any venue early in the development process. In practice, that means acousticians and sound system designers should be brought into the design team from the start, preferably as early as the programming phase, to ensure that acoustics and sound reinforcement are included in infrastructure planning.

I) ACOUSTIC CONCEPTS

The Difference Between Light and Sound

Because human senses are analogous in many ways, there is a mistaken tendency to think of sound as being similar to light, giving the impression that all you need to do is "illuminate" an area with sound. Unfortunately, this analogy falls short because of the basic physics involved.

The airborne wavelengths that we perceive as sound are much longer than the electromagnetic waves that we sense as light. When multiple light sources are beamed at the same place in a room, the

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During the construction phase of Greater Grace Church near Detroit, façade openings for vertical line array loudspeakers were still visible.

light level increases without producing detectable visual distortion. By contrast, multiple sound waves projecting into the same place within a room can interfere adversely with each other, and can even cancel each other out, unless the room acoustics and sound system are specifically designed not to do so. This interference can remove important portions of the sound spectrum, can result in different sound quality at different spots within the room, and can smear the time arrival of the sound. All these factors can make music muddy and unappealing and can make speech unintelligible.

Common causes of such interference include reflections and loudspeaker interaction issues.

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When Roswell United Methodist Church upgraded the sound system in its 2,000-seat sanctuary, matching the sound system to acoustics resulted in uncompromised intelligibility from the podium and crystal clear sound from the choir, organ and praise band.

Sound Reflections

Solid straight surfaces, like fronts of balconies, can create reflections. In the case of a balcony at the rear of a theater or auditorium, the sound reflected back into the audience makes it difficult for those seated between the stage and balcony to understand speech because they hear both the original sound and the echoes, which are reflected sounds that reach the ear at a later time than the original sound coming from the stage. The result is garbled, unintelligible speech.

Room and Wall Shapes

Concave, round shapes, including parabolic walls and domed ceilings, are among the worst shapes for a room in which speech is important. The concave shape focuses sound into specific areas, making those areas acoustically louder than other parts of the room and producing strong *late reflections* that are out of time-sync with the original sound from the stage or front loudspeaker. This causes intelligibility problems. Dividing concave surfaces into *multiple convex surfaces* can *diffuse* (or split) the reflected wave into a number of smaller waves going in different directions, making each less bothersome to the audience.

Acoustical Treatment

Acoustically absorptive materials tend to be frequency-selective, meaning that some materials will absorb only high frequency sounds while others will absorb both high frequencies and the midrange frequencies that span human speech. It is important to ensure that the material selected for wall coverings, window treatments, acoustical baffles, etc., absorbs the intended frequencies in just those areas where absorption is required. Other treatments, such as using *diffusers* to split up the sound wave, might be more effective at times. A qualified acoustician can advise about which is the most effective treatment for a specific problem.

The 30-Millisecond, 30-Foot Principle

When do reflections become bothersome to the listeners? When a reflected sound's path length is 30 feet longer than the original sound, the reflection will hinder intelligibility. That's because the human brain integrates sounds that arrive within 30 milliseconds (ms) of each other to perceive a single sound. Reflections that arrive more that 30 ms after the original sound are perceived as echoes, which interfere with definition of music and comprehension of speech.

Sound travels at approximately *one foot per millisecond*. That allows us to convert the 30 ms time figure into a distance of 30 feet. When the total path of a reflected sound – that is, the distance the sound travels from the listener to the reflective surface and back to the listener – is more than 30 feet, the reflection will hinder intelligibility. For example, reflections from a wall located 10 feet behind the listener are

Who Provides What Service?

Industry terminology
is not always consistent
regarding which companies
provide which service, and what
their businesses are called. Some
firms specialize in just one
of these services, while
others package together
multiple services.

Firms that only design sound systems are commonly called *Audio Consultants* or *Electro-Acoustical Consultants*.

But some companies provide vertically integrated services. For example, it is common for a single *Acoustical Consultant* firm to provide both acoustical and sound system design services.

Audio consultants who also design video systems might call themselves *A/V Consultants*. Firms providing a wide selection of technical design services such as security, telephony and/or information systems are often referred to as *Systems Consultants*.

Companies that combine sound system design with installation services are typically called *Design/Build Systems Contractors*. They sometimes provide the design service in return for getting the installation contract, making this an economical choice for negotiated jobs that will not be going out to bid. They provide a single point of accountability, yet their design

services may not be as well developed as specialty system design firms. When design/build of audio is combined with other installed systems, the contractors are often referred to as *Systems Integrators*. These companies can sometimes split their design and build functions, if needed, to fit the requirements of the project.

How to Choose

There is no universally recognized certification or licensing for acousticians or sound system designers. It is therefore probably best to look for a firm with experience in the same type of facility as your project and with good references. Many firms specialize in certain types of applications – for example, churches or auditoriums or school music rooms – while others are generalists who may have experience in many project types. Proven capability and positive references from previous work, both from the design team and from the end-users, may be the best indicators.
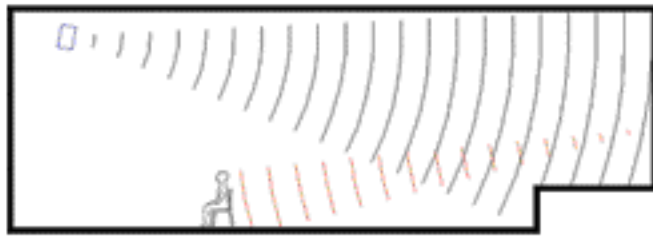
Reflections from the back wall can be problematic, degrading speech intelligibility and clarity of music.

usually OK because after the original sound passes the listener, it takes 10 ms to get to the back wall and another 10 ms for the reflection to travel back to the listener, for a total of 20 ms. However, that same wall located 20 feet behind the listener can be a real problem, because 20 ms from the listener to the wall and another 20 ms back to the listener totals 40 ms, which breaks the 30-ms guideline.

Solutions could involve applying absorptive materials to the reflecting surface to reduce the amount of reflected sound, altering the shape of the reflective surface to break up the coherence of the reflected wave, or redesigning the sound system so that it does not excite the reflection in the first place.

By contrast, *early reflections* hitting the ear within the 30 ms guideline – particularly those coming from the sides, called *early lateral reflections* – can enhance the spaciousness of the sound, giving the room a warm ambience. Some performance halls are designed with close sidewalls to improve the sound by increasing the number and density of early lateral reflections.

Noise Control

Noise from air handling systems and adjacent spaces can also reduce the quality of sound within a room and should therefore be examined and baffled if necessary.

II) SOUND SYSTEM PRINCIPLES

The acoustical properties of the room and plans for the sound system should be carefully matched early in the design process to avoid costly and potentially unsightly acoustical remedies later.

The Audio Spectrum

Audio wavelengths are measured in cycles per second, or hertz (Hz). So, for example, 440 Hz, the frequency of the A note above middle C on a piano, equals 440 cycles per second. The audible spectrum for humans is 20 Hz to 20kHz (20,000 Hz). For live or recorded music, the entire audible spectrum needs to be considered. For speech intelligibility, sound system designers need to pay particular attention to the middle range of frequencies, generally from 500 Hz to 4kHz. However, even for speech-only systems, the frequencies below and above this band are important for imparting a natural sound character to voices, and for avoiding boomy or thin speech character.

Each portion of the audio spectrum imparts its own challenges due to differences in wavelengths. High frequencies have short wavelengths. A 20kHz wave is ½-inch (12 millimeters). Lower frequencies have longer wavelengths. A 20 Hz wave is 50 feet (12.7 meters). These wavelengths behave very differently.

Obstructions & Line-of-Sight

Whereas the long wavelengths of low frequencies can *diffract* (or bend) around objects, the shorter wavelengths of high frequencies are blocked by objects in their path, leading to portions of the audio spectrum disappearing for listeners seated behind an obstruction.

For listeners to hear midrange and high frequencies clearly in a theater or auditorium, loudspeakers need to placed in a straight line-of-sight position to all members of the audience. Naturally, this means that the loudspeakers tend to be visible to the audience and thus have the potential to interfere with the aesthetics of a room's design. However, the visual impact can be minimized by a number of methods, including covering the speakers with an acoustically transparent façade. Any material that is being considered should be tested for sound transmission prior to installation.

Then again, hiding the system is not always best, nor is it popular anymore. Some loudspeakers, such as vertical line arrays and other cleanly rigged systems, may be acceptably exposed. In fact, the loudspeaker design and color can be effectively incorporated into the overall room design to complement other elements and overall form. Whether speakers are hidden or exposed, identifying any visibility issues early in the design process can enhance the total ambience of the facility, both visual and acoustical.

Pattern Control and Loudspeaker Size

Sound system designers choose loudspeakers whose coverage patterns match the listening area. Poor pattern control results in uneven sound coverage, a tendency for the sound system to feed back, destructive multiple reflections, tonal irregularities, and poor intelligibility.

Unfortunately, it typically takes large speakers to control coverage over a wide spectrum, down to a low enough frequency. Loudspeaker engineers generally achieve controlled coverage via horns or loudspeaker driver-spacing interaction. Both require the speaker to be large in order to achieve good pattern control.

Point-and-Shoot and Vertical-Line-Array Loudspeakers

There are many different types of loudspeakers and speaker arrays, each with its own pros and cons. *Point-and-shoot* loudspeakers are traditional speakers, each covering a certain area of the audience. They can be used singly or in arrays of multiple loudspeakers. However, arraying requires a thorough understanding of loudspeaker array theory, because unintended wave interactions can create problems.

Vertical-line-array loudspeakers are becoming popular in installed applications due to improved front-to-back evenness of coverage and narrow vertical coverage angles, resulting in increased throw distances and less leakage of sound to the stage and ceiling. Line arrays tend to be more expensive and may not be appropriate for certain spaces.

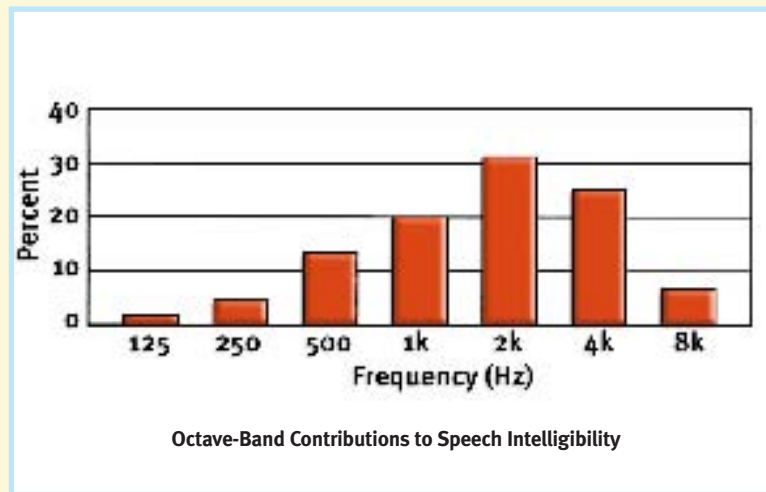**Octave-Band Contributions to Speech Intelligibility**

Special problems arise in shallow rooms, where the stronger throw of sound to the back wall produces undesirable reflections, and narrow rooms, where the typically wide horizontal coverage angles of these speakers tend to splatter sound onto the sidewalls.
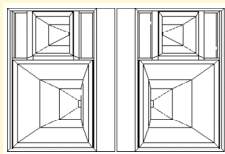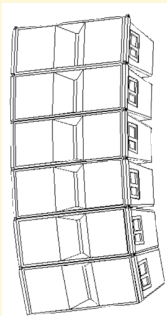
A vertical-line-array loudspeaker system (left) versus a horizontal array of "point and shoot" loudspeakers (above). The right choice can be critical.

Delay-Fill Speakers and Distributed Sound Systems

Fill speakers allow shadowed areas, such as under balconies, to be covered with sound. The signal to fill speakers needs to be electronically delayed so that the sound arrives at the listener's ears in time-sync (i.e., within 30 ms) of the sound from the main speakers. Delay-fill speakers can also be used part way back in the room to cover the immediate area around them. For example, in fan-shaped rooms it is common to see one ring of main speakers near the stage augmented by a second ring of delay-fill speakers part way back in the room, and perhaps a third delay-fill ring even farther back. These can then be augmented by under-balcony delay speakers in the shadowed areas that none of the other speakers cover.

Distributed sound systems consist of multiple speakers. A common type of distributed system uses speakers projecting down from the ceiling, each covering a specific area. Distributed systems are common in places like offices, yet are also used in ancillary areas of performance venues.

Sound System Optimization

In addition to loudspeakers themselves, sound systems require properly designed drive electronics, which must be adjusted using proper equipment and techniques. These systems provide specific tonal compensation (equalization), time delay and crossover functions. However, electronic adjustments cannot correct many types of acoustical problems, especially reflections in the form of echoes or reverberation. Equalization should be considered the "frosting on the cake" in a well-designed room and sound system.
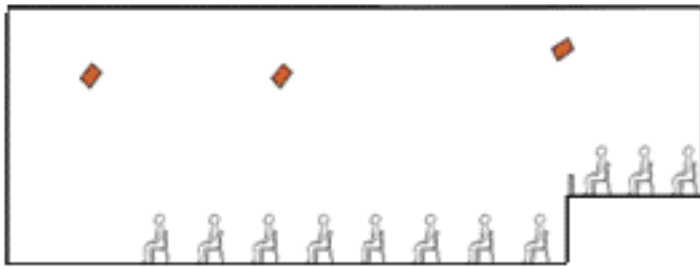
Multiple delay-fill loudspeakers bring the sound close to the listeners while reducing troublesome reflections sometimes caused when a single speaker is employed to cover too large of an area.

III) THE DESIGN TEAM

Acousticians

A good acoustician is vital for early acoustics issues such as the shape, noise control, and proportions of a room. They can advise, for example, on ways acoustics can support congregational participation in a church by allowing worshipers to hear each other's participation adequately. They can ascertain the target reverb time (the time it takes for a sound to disappear in the room) to match the use of the room. Too short of a reverb time makes a room sound lackluster, while too long of a reverb time makes speech unintelligible. Their input is crucial in the selection and placement of finishes, seating and any special treatments of surfaces. It can be difficult, expensive or even impossible to fix bad acoustics after the fact, and subsequent acoustical bandages can have an unwanted visual impact.

Sound System Designers

Sound system designers are also key team members. They should be brought in early to assess system compatibility with room acoustics and to recommend preliminary loudspeaker placement, the location of the sound console – preferably within the audience area – and closets, racks, or other space for electronic components.

Computer-based tools enable sound system designers to spec a loudspeaker system before a room is ever built. Designers can also assess the impact of wall angles and materials selections, and can predict what problems will occur. Identifying these issues early in the process will allow changes to be made on the drawings rather than retrofitting completed construction at additional cost. Several of these computer-based design programs enable the user to hear an approximate simulation of the acoustic

model through a process called auralization. It is important to note that auralization is best used not as an exact prediction of room sound, but rather to evaluate the relative acoustical impacts of various options to determine which may be most desirable.

The required installation/hang locations for loudspeakers can also be determined and aesthetic issues considered to ensure that they will fit the appearance criteria of the facility. Later, the sound system design will be refined in conjunction with the function and needs assessment of the facility, expanding the system design to include the electronics, cable routing, etc. Direct coverage predictions should be required before a loudspeaker system gets installed to verify even coverage. In jobs where the sound is particularly important, an additional investigation of how reflected sounds behave in the room is worthwhile.

For venues where sound is central to the proper functioning of the facility, speech intelligibility and music clarity are vital. A good sound system in a room that is designed for music performance or spoken word is important. This overview is intended to impart a basic working knowledge of acoustics and sound system design principles and practices. Yet professionals must consider many additional factors in order to make the space successful. A better experience for facility owners, operators, managers and their guests can be assured with proper planning from a knowledgeable team of architectural, acoustical and sound system design professionals. ●

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For more information on these topics, refer to the following books:

Sound System Design
JBL Audio Engineering for Sound Reinforcement, John Eargle and Chris Foreman, Hal Leonard Corp, 2002.

Acoustics
Acoustics – Architecture, Engineering, the Environment, by Charles M. Salter Associates, Inc., William Stout Publishers, 1998.

Architectural Acoustics – Principles and Design, by Mehta, Johnson, and Rocafort, published by Prentice-Hall, 1998.

Architectural Acoustics by M. David Egan, McGraw-Hill, Inc., 1988.