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## Canadian Building Digest

Division of Building Research, National Research Council Canada

**CBD 92**

# Room Acoustics – Design for Listening

*Originally published August 1967.*

*T.D. Northwood*

### **Please note**

This publication is a part of a discontinued series and is archived here as an historical reference. Readers should consult design and regulatory experts for guidance on the applicability of the information to current construction practice.

This Digest is concerned with the design of auditoria, i.e., of rooms in which the objective is communication from a source (a speaker or performer) to a group of listeners. In all such rooms, ranging from classrooms to concert halls, the primary consideration must be the communication process. The occupants must be able to hear and understand the message being delivered or the room will be a failure.

The success or failure of an auditorium is determined by its size and shape, and by the spatial relationship between source and listeners and the surfaces that surround them. Thus, the acoustical result is affected from the moment pencil is first put to paper. The purpose of this Digest is to help the designer in these early stages, not to cover the detailed acoustical design (which is better left to the expert), but to describe the basic communication process and to show how it is affected by room design. Emphasis will be on speech communication, but the special features of musical performance will also be touched on.

### **Speech and Hearing**

Briefly, speech consists of a sequence of vowel sounds punctuated by consonants. Most of the acoustic power is produced by the vowel sounds at frequencies from 250 to 500 hertz (cycles per second). It is the modulating effects of the consonants that provide most of the information, and these involve sounds of higher frequencies.

The degree of intelligibility depends on the difference in level of the speech signal and the ambient noise at each frequency from about 250 to 4000 Hz. When, in any frequency range, the lower levels become submerged in the ambient noise, one begins to lose intelligibility. The sound travelling directly from speaker to listener would be insufficient beyond about 30 ft for typical levels of ambient noise. For communication beyond this range the boundaries of the auditorium have the function of redistributing usefully the energy radiated from the source.

The duration of individual speech sounds varies from a few milliseconds to a few hundred milliseconds. For good intelligibility the listener must be able to resolve sounds as short as about 50 milliseconds. Hence, for useful reinforcement, reflected energy must reach the listener within about 30 milliseconds of the direct sound. As the speed of sound in air is about 1100 ft/sec, this means that the difference in path length for direct sound and reinforcing reflections should be no more than about 30 ft.

Although reflected sounds are essential to hearing in an auditorium, the resultant sound field may be quite complicated, since the various reflections arrive from different directions and at different times. The listener locates the source satisfactorily if the first-arriving sounds reach him from the direction of the source. Later arrivals from other directions do not interfere with the localization process, even if they are higher in level by as much as 10 dB. This is important in the design of electronic reinforcement systems.

## **Music**

Musical sounds resemble speech in that they consist of a series of transients varying in duration, intensity, and frequency content. The dynamic range from the loudest to the softest musical sound is more than for speech, but the minimum levels are quite comparable. The frequencies involved extend over a considerably wider range than for speech, ranging from about 30 Hz for some musical instruments to about 10,000 Hz to encompass the high-frequency components that characterize different instruments.

The process of listening to music is also rather similar to that for speech, although again there are some differences of degree. In music as in speech the sounds must be heard in sequence and with sufficient resolution. But the duration of musical sounds is generally longer, and a certain amount of blurring of individual sounds is considered to be an enhancement. The exact nature of this enhancement is rather elusive and makes a music hall as much a work of art as a matter of acoustical technique.

## **Reverberation**

It has been noted that short-delay reflections provide essential reinforcement of direct sound. The reflection process does not stop, however, after the first desirable reflections have reached their destinations. The sound waves continue to be reflected again and again, losing a fraction of their energy at each reflection. The eventual result is a relatively uniform distribution of "reverberant" sound throughout the room. For speech (but not necessarily for music) this reverberant sound is a nuisance, since it tends merely to mask the low-level portions of the transients that provide intelligibility.

The rate at which the reverberant sound dies away is measured by the *reverberation time*, defined as the time required for the reverberant sound to diminish by 60 dB. The reverberation time can be calculated, approximately, from the formula,  $T = 0.05 V/A$ , where  $V$  is the room volume, and  $A$  is the absorption in sabins, a sabin being the absorption of a square foot of perfect absorber.

Certain values of reverberation time have been found acceptable for various applications: for speech the middle-frequency reverberation time should be about one second or less; for solo instruments and chamber music, 1.0 to 1.5 sec; for symphonic music, 1.5 to 2.0 sec; for church music, 2.0 to 2.5 sec. Generally, longer times are accepted in larger halls and with larger musical ensembles. The time should be nearly constant with frequency, although for music a slight rise at low frequencies is desirable.

These reverberation time values provide one useful design criterion, but they are usually secondary to a careful analysis of room shape and distribution of reflected energy. Generally, one makes a preliminary calculation of reverberation time when the room volume and seating capacity are established. This provides a rough estimate of the total absorption that must be added. As the detailed design proceeds the absorption requirements are met by placing absorbing materials where they will do the most good or the least harm.

## **Sound Absorption and Reflection**

To a first approximation, what happens to a sound wave when it reaches a surface depends upon the absorption coefficient of the surface, i.e., the fraction of incident sound power that it absorbs. Massive impermeable surfaces such as concrete or masonry have absorption coefficients less than 0.05 and are regarded as practically perfect reflectors. Less massive surfaces such as thin plywood and plasterboard may be similarly reflective at middle and high

frequencies, but may have absorption coefficients as high as 0.50, due to panel resonances, at low frequencies.

On the other hand, a thin porous material mounted against a hard backing will be mainly reflective at low frequencies, but will increase in absorption efficiency with increasing frequency. Carpet and acoustical plaster are typical examples of this type of surface. Draperies also tend to absorb mostly at high frequencies, being practically transparent at low frequencies.

To achieve a constant reverberation time, it usually is necessary to adjust particularly the low and middle-frequency absorption. An efficient absorbing system in this range often consists of a slotted or perforated screen over a backspace containing porous material. The backspace, the perforated surface and the absorptive material constitute a broadly resonant system that can be tuned to whatever frequency range is desired. Some commercial acoustical materials combine two of the above features: a perforated or "fissured" facing over an absorptive back layer; their absorption characteristics can be varied by varying the backspace and mounting system.

Generally, the audience provides most of the absorption, amounting to about 5 sabins per person and nearly constant over the important frequency range. It is an unfortunate result that acoustical environment depends strongly on audience size. Well-upholstered seats and carpet, both partially masked when an audience is present, help to level out the variation with audience.

### **Geometrical Acoustics and Room Shape**

If reflecting surfaces are wide enough and smooth enough they reflect sound specularly in the same way that a mirror reflects light. Surfaces smaller than a few wavelengths or with irregularities greater than  $1/4$  wavelength tend to scatter or disperse sound, more or less like point sources.

As the sounds we hear have wavelengths ranging from about 50 ft to a fraction of an inch, most surfaces will be specular reflectors over only part of the range. For the middle frequencies, of special importance to both speech and music, these conditions are met by a surface wider than about 4 ft and with surface irregularities of less than an inch or so. For such surfaces one may use the methods of geometrical acoustics, closely analogous to geometrical optics. By simple ray-tracing techniques one can examine the total distribution of sound from a source to all parts of an enclosure. The main difference from the optical case is that the transit time of sound waves must be taken into account: sounds arriving by several paths do not reinforce each other unless they coincide in time as well as in space.

To study the reflections from various room surfaces the procedure is to consider rays from the source to the surfaces in question. For a plane surface the reflected ray is then drawn in accordance with the rule that the angle of reflection equals the angle of incidence (Figure 1). For graphic analysis it is frequently convenient to replace the original object by its mirror image (also illustrated in Figure 1). This automatically fulfils the above rule. Then it is easy to draw from the image the whole set of reflected rays for the given surface.

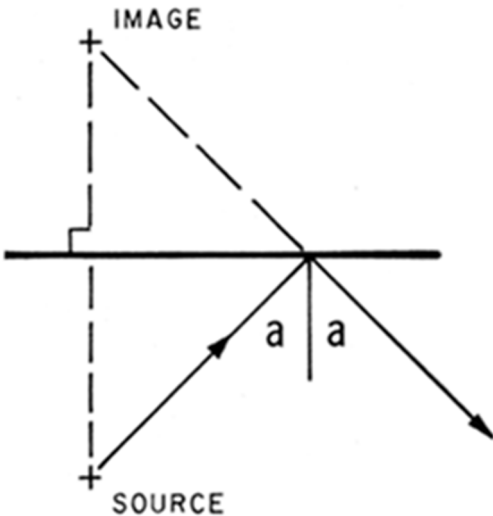


Figure 1. Reflection from plane surface.

Curved surfaces may be dealt with in the same way by considering each small segment to be a plane. It will be found that sound reflected from convex surfaces diverges over a wide angle, whereas sound reflected from concave surfaces tends to converge. A convergent beam results in amplification of the sound and must be dealt with rather carefully. A slightly concave surface may be quite useful for deliberately providing some amplification of the sound reaching a distant seating area, but extended closed curves such as cylindrical or spherical enclosures may focus the sound in particular areas. The first stage in analysis of a proposed room shape is to trace the first reflections from the major room surfaces, considering both the time delays and the energy distribution. The seating areas in most need of reflected sound are, of course, those farthest from the source.

Ideally, the ray-tracing technique should be extended to multiple reflections, following each portion of the source energy until it reaches the seating area or some other absorptive surface. The principal purpose of this is to guard against the possibility of a cluster of arrivals that might in sum be strong enough to constitute a serious echo.

Another echo effect to guard against is the prolonged series of reflections associated with a pair of large parallel surfaces. A single impulse produced between the surfaces tends to be reflected back and forth between them, the successive transits being heard as a series of pulsations; hence, the term "flutter echo." The phenomenon is quickly damped out if either surface is sufficiently absorptive or irregular. There is usually no problem between a horizontal ceiling and floor if the latter is broken up by furniture and people, but it is a common one with parallel side walls.

### Sound Reinforcement

Properly designed rooms smaller than 50,000 cu ft should need no electronic reinforcement for most speakers and most musical performances. A good speaker can manage comfortably in good halls as large as 200,000 cu ft, but beyond this electronic reinforcement is usually desirable for speech.

Except for the most colossal enclosure one should not, however, rely on electronic aids to solve the whole acoustical problem. Electronic reinforcement is most successful when used to extend and embellish the performance of a good auditorium. Properly used, it leaves the audience unaware of its existence.

The design of the reinforcement system should be part of the design of the hall itself. Loudspeakers may be thought of in the same way as the principal reflecting surfaces in that they supply energy to reinforce the direct sound. There is one notable difference: the sound leaves the loudspeaker at practically the same time as it leaves the original source. Thus, to

avoid interfering with the listener's sense of localization the path from the loudspeaker to the listener should be slightly longer than the direct path.

Generally, this condition cannot be met for an entire audience, but it is satisfactory to use a directional loudspeaker, placed near the source end and as high as possible, and tilted so as to serve the most remote part of the audience. In very large halls it may be necessary to distribute loudspeakers throughout the audience area. This can still sound natural if artificial time delays are introduced in the electronic system.

Another consideration in loudspeaker placement is proximity to the microphone. In any reinforcement system there is a limit to the possible amplification beyond which sufficient sound feeds back from loudspeaker to microphone to sustain a continuous oscillation. To avoid this the loudspeakers should be far enough from the microphone and suitably oriented.

### Noise

It was noted at the beginning that what one hears in an auditorium is limited by background noise. Apart from audience noise there are two common sources of extraneous noise: noise transmitted from adjacent areas, through walls, ceilings, door and windows; and noise from ventilation systems. The first involves obvious questions of site arrangement, layout, and sound insulation that have been discussed elsewhere ([CBD 10](#), [CBD 51](#)). The second involves noise reduction measures that should be familiar to any mechanical consultant, but he must be given a specification to meet. Using the well-known Noise Criterion Curves ([CBD 41](#)), an appropriate specification might be NC-20 to NC-30, the higher value being adequate for small rooms, the lower one for large rooms.

### Examples

It may be instructive to consider as a simple example a small classroom suitable for about 30 students. The acoustical problems are not severe in this case and a rectangular pattern may be appropriate. A reverberation calculation will indicate that some absorption treatment will be needed to reduce the reverberation time to the desirable 0.7 sec. The temptation might be to solve this and other problems by installing an acoustical ceiling, but the ceiling is ideal for providing reinforcement of the direct sound. Absorption is best introduced on the upper part of the rear wall, thus avoiding an echo back to the speaker. Similarly, one or both of the side walls might be treated, especially near the front where there might be a flutter echo. A band around the edge of the ceiling is a third region that could be made absorptive if more absorption is needed.

As a second example, consider a larger lecture hall, accommodating perhaps 300 students. In this case it is desirable to shape the room carefully so that as much as possible of the speech energy will be usefully redistributed, especially to listeners in the rear seats. A fairly simple longitudinal section is shown in Figure 2; in plan it might be broadly fan-shaped, with the walls designed to act in part as reflectors. The distribution could be further improved by breaking the ceiling into more segments, oriented to direct more of the reflected sound to the rear half of the seating area. Other factors such as structure, lighting, and ventilation also influence the ceiling shape, but they should not be permitted to impair the acoustical design.

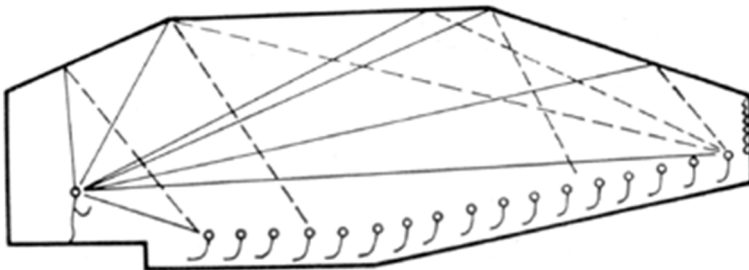


Figure 2. Shape considerations in lecture theatre design.

It will be found necessary to add some absorption to bring the reverberation time down to about one second. Again, the first area to treat is the rear wall; the remainder can be placed on certain portions of the side walls that are difficult to shape for useful reflections.