Editorial

ACOUSTICS . . . SCIENCE OR ART? The article on Architectural Acoustics by David L. Klepper in this issue again raises this question. The construction of many music halls, all of which designs featured the work of acousticians, have been scored by public, press and audio professionals as unsatisfactory. One hall is too dry, another is too reverberant, a third has not enough intimacy. Fault will be found with any hall.

Does this mean that acousticians operate in the dark . . . that their results are produced by *experimentation* rather than *science*?

Not at all. Modern acoustics is very much a science. Very little that is done today is of the cut-and-try school. The acoustician involved in designing a hall or studio can create pretty much what is wanted. The core of the problem seems to be that the architects and underwriters of halls have broad ideas of what the room is to do. No one builds a specialized hall or studio; a variety of jobs must be accommodated.

A particular studio may be used mainly for small vocal groups, but since it might occasionally house eighty-piece orchestras, it must also be adapted for this need. A studio that fits both requirements can be built . . . but it will be involved and expensive. So the acoustician, against his better judgment and advice, compromises the room so that it is at least acceptable for both extremes. Then, the room is just that – a compromise. It is not highly satisfactory for either of our examples.

Thus the acoustician becomes a scapegoat for the studio's inadequacies, when in fact he could have created an acceptable situation had he been given a limited goal and a free hand.

There is a very real lesson to be gained from this. Many of you will be needing rooms that require specialized acoustic treatment. This should not be left to word-of-mouth chance. The acoustician is a proper part of the professional audio scene. His help and advice can multiply the usefulness of a room, thus increasing its potential for income. And this will offset many times the cost of acoustical consulting. *L. Z.*

Architectural Acoustics

David L. Klepper

Certain ground rules must be followed to design a studio to specific acoustic needs. These practical facts suggest how to build or modify rooms so that the best can be obtained from them.

Part One: ROOM ACOUSTICS

THE professional worker in audio is involved with acoustics, regardless of his specialty within his field. Indeed, the fields of audio and acoustics overlap more than they are separate and distinct. The acoustics of recording and broadcast studios, theaters, concert halls, and other performing spaces affect the work of the recording and broadcast engineer—while the acoustics of any space requiring an electronic sound amplification system will affect the performance of the system and the work of the system designer, installer, and operator.

A theater, concert hall, auditorium, or a radio or television studio should be designed acoustically: first to form a good *room-acoustic* link between the live sources of speech and/or music, and the live listeners and/or microphone(s); and second to exclude noise. Both the room-acoustics and noise-control aspects of architectural acoustics have been under continuous development for many years. The goals of the room-acoustics design may be stated as:

- Insuring an even distribution of sound energy throughout the space.
- Controlling discrete echoes, rapidly repeating echoes (flutter-echoes) and bunching of the normal modes of vibration of the rooms which might emphasize certain frequencies.
- Providing the proper reverberation time characteristics.
- Assuring the proper ratio of reverberant-to-early sound, related to the shape of the reverberation decay curve and particularly important in spaces where live music is heard by live listeners.
- Providing a short enough initial time-delay gap, for early reflections, again important in *live-music* spaces.

Diffusivity and Echo Control

Even sound distribution and satisfactory control of echoes and normal modes is achieved where there are no extreme variations in sound pressure either as the frequency of the signal or the position in the room is varied. Diffusivity can be accomplished by avoidance of parallelism in the basic shape of the room, as in FIGURE 1, or large-scale modulations of basically rectangular shapes, as in FIGURE 2. The popular polycylindrical diffusers (FIGURE 3) are one form of "break-up" that can be added to basically rectangular-shaped rooms.

Where large, concave or flat surfaces are essential because of architectural or other planning considerations, echoes may be controlled by sound-absorbing treatment. Usually, however, diffusion by surface break-up and shaping should be considered first and the sound-absorbing treatment limited to that required for reverberation control.

Elements added to basically rectangular rooms for sound diffusion must be approximately equal or larger in scale compared with the wavelengths of sound energy being controlled. (The wavelength of a 100 Hz signal is 11.3 feet.) For speech studios a designer might restrict diffusion to the range above 200 Hz (5.65 ft.), but for music studios the range down to 50 Hz (22.6 ft.) or even lower — to the 20 Hz lower limit of human hearing — may be important.

In many auditoriums and concert halls, balconies or applied decoration in the form of statues. etc. are "natural" sound-diffusing elements.

Reverberation Time

We define reverberation time as the time required for sound to decay to one-millionth of its value (60 dB) after cessation of the sound source. In any real room it usually varies as a function of frequency and may be predicted accurately by the ratio of the volume of the room to the total sound-absorption present, according to the following formula[1]:

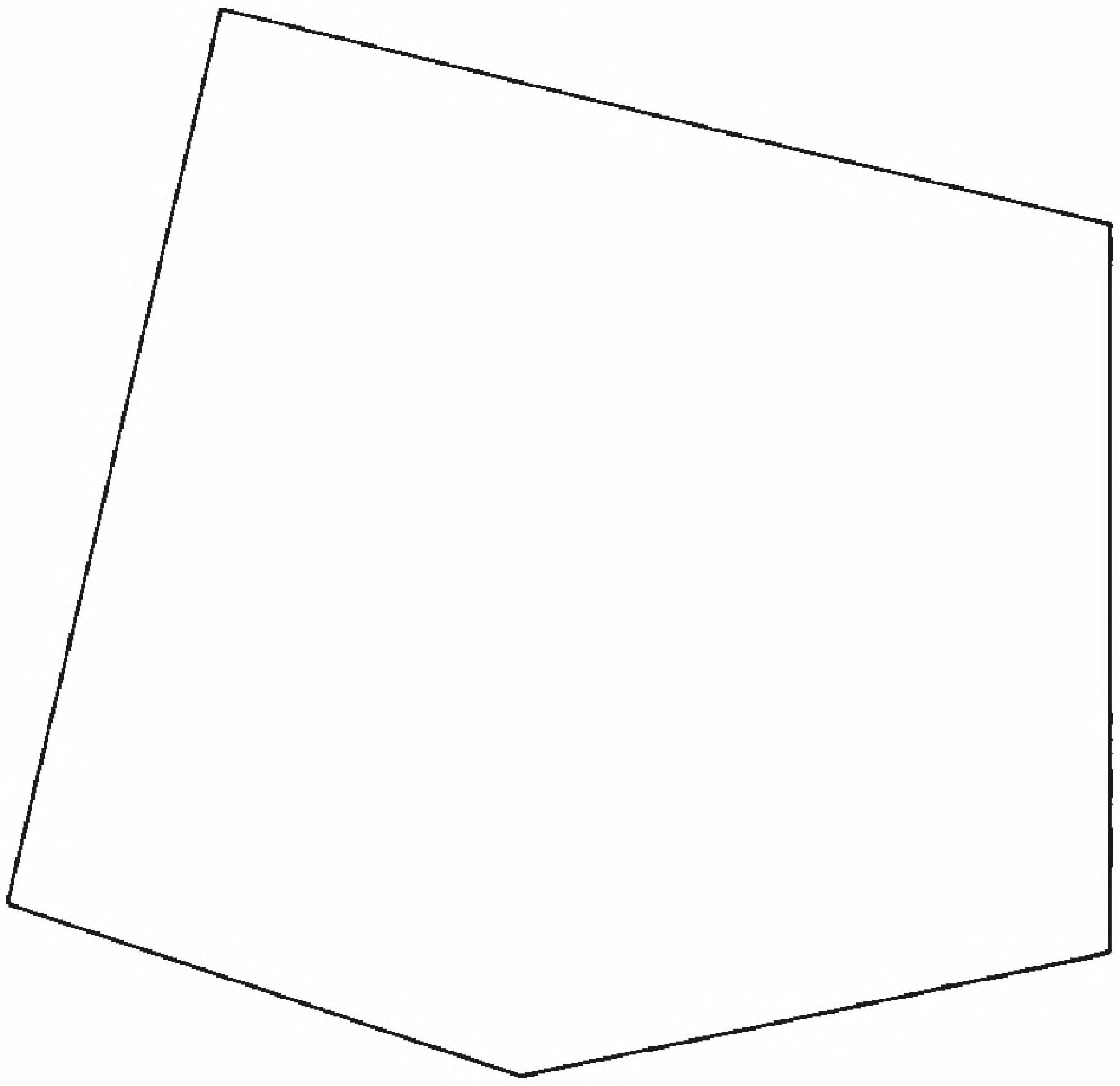

Figure 1. A non-rectangular plan for a study.

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[1] This equation is called the Sabine equation after Wallace Clement Sabine, father of modern architectural acoustics. It appears generally applicable for must diffuse-large spaces, although the Norris Eyring equation or other modifications of Sabine's original equation are perhaps more appropriate for small or very dead rooms.

$$R_t \text{ (reverberation time)} = \frac{0.049\ V}{S\alpha}$$

Where V = room volume
S = room surface area
α = average absorption coefficient
$S\alpha$ = total sound absorption

Although early studios were uniformly dead, there has been a trend from the early days of broadcasting to the present for more reverberant studios, particularly for music performance.

Beranek's suggested criteria for speech, general, and music studios still appear to be generally applicable and are illustrated in FIGURE 4. Large music studios should have much the same reverberation time characteristic as a fine concert hall. Speech studios should have essentially no audible reverberation with less or equal reverbation time at frequency extremes (low-frequencies and high-frequencies) as compared with mid-frequencies.

General studios may be a compromise between speech studios and music studios. Regarding auditoriums for "live" listeners, experience suggests the following mid-frequency reverberation times for different uses:

	Optimum	*Possible*[2]
Lectures	0.9 – 1.1	0.5 – 1.4
Drama (theaters)	0.9 – 1.4	0.5 – 1.6
Musical Comedy	1.2 – 1.5	1.0 – 1.7
Opera	1.5 – 1.8	1.4 – 2.0
Instrumental Recitals and Chamber Music	1.4 – 1.8	1.0 – 2.0
Orchestral Concerts	1.8 – 2.0	1.4 – 2.5
Vocal Recitals	1.5 – 1.8	1.4 – 2.0
Choral and Organ concerts (liturgical music – the upper limit depends on the type of music)	2.0 minimum	1.7 minimum

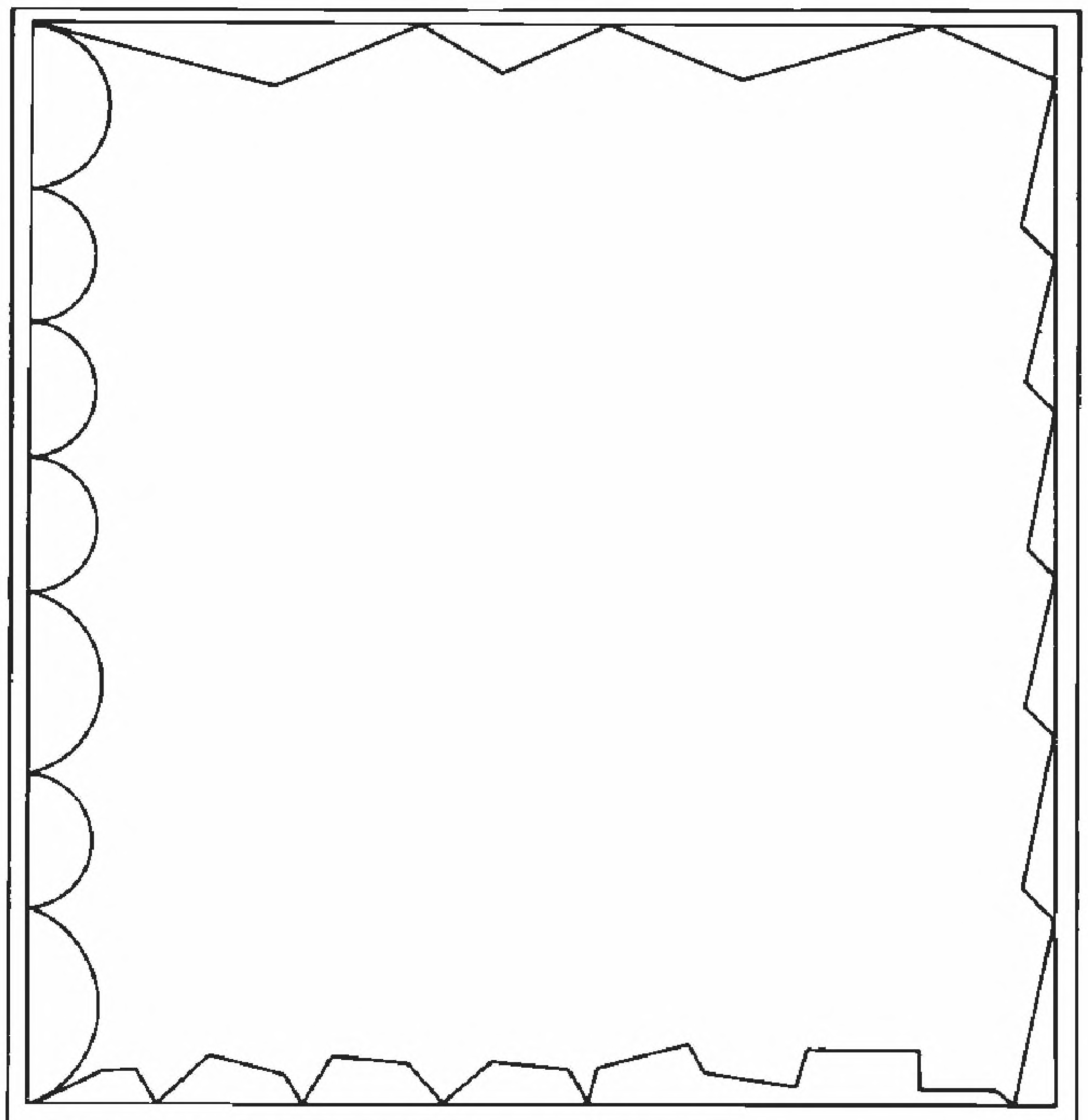

Figure 2. Sound diffusing wall modulations of several types applied to a rectangular room.

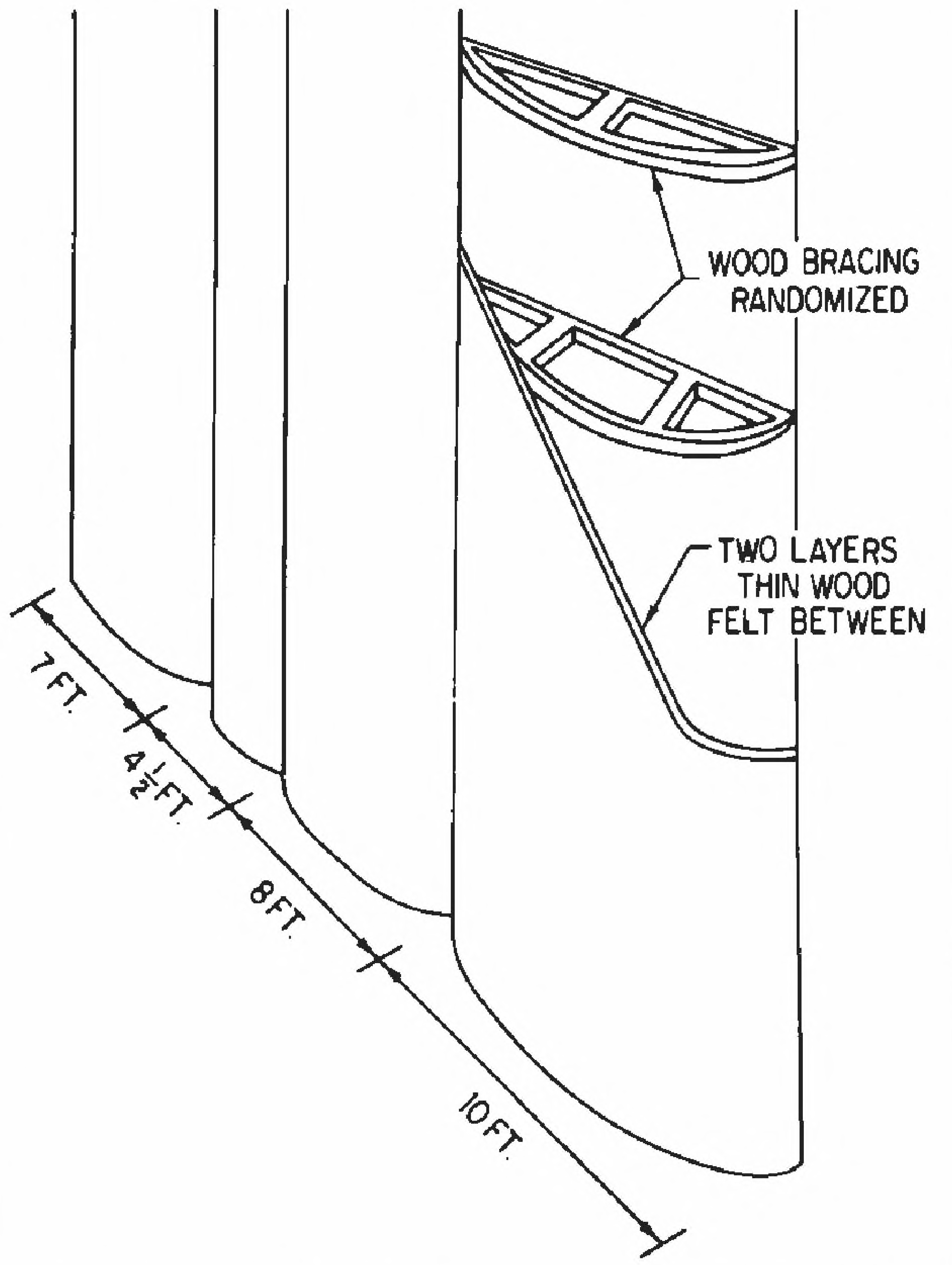

Figure 3. Typical polycylindrical diffuser construction. The diffusing effect of a cylinder is maximum when diameter equals one-half wavelength, and a combination of different radii will provide optimum diffusion over a wide range. The construction shown also provides low-frequency absorption.

Occasionally a reverberation time calculation will reveal a studio or auditorium on the "dead" side (too low a reverberation time), even without any applied sound-absorbing treatment. For example, the calculated reverberation time for a studio planned for music broadcasting may be under 1.5 seconds at mid-frequencies, even with all interior finish materials hard and sound-reflecting. The reason may be a relatively low cubic volume (interior volume less than say 40,000 cubic feet), with the predicted sound-absorption of the 100 members of a full symphony orchestra present.

Economics may dictate the design of studios or halls below optimum size. Under these conditions the wise designer or acoustical engineer will often refrain from attempting to make the hall or studio as live or reverberant as possible within the available volume, because under certain conditions in small halls or studios, he would be concerned that the space would simply be too loud for proper performance conditions. Instead, particularly in studio situations, he might choose to provide a relatively dry acoustical environment to be supplemented by electronic reverberation devices, either within the hall itself (for performers, listeners, *and* recordings) or for recordings alone.

We have been discussing mid-frequency reverberation time goals for various spaces. These are reverberation times measured in the 500 – 1000 Hz range. The variation in reverberation as a function of frequency is also very important; and it is a good measure of the "frequency response" of the room. For example, a concert hall with a reverberation time of 2.8 seconds at 125 Hz, 2.0 seconds at 500 and

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[2] Good results possible provided other parameters are optimized.

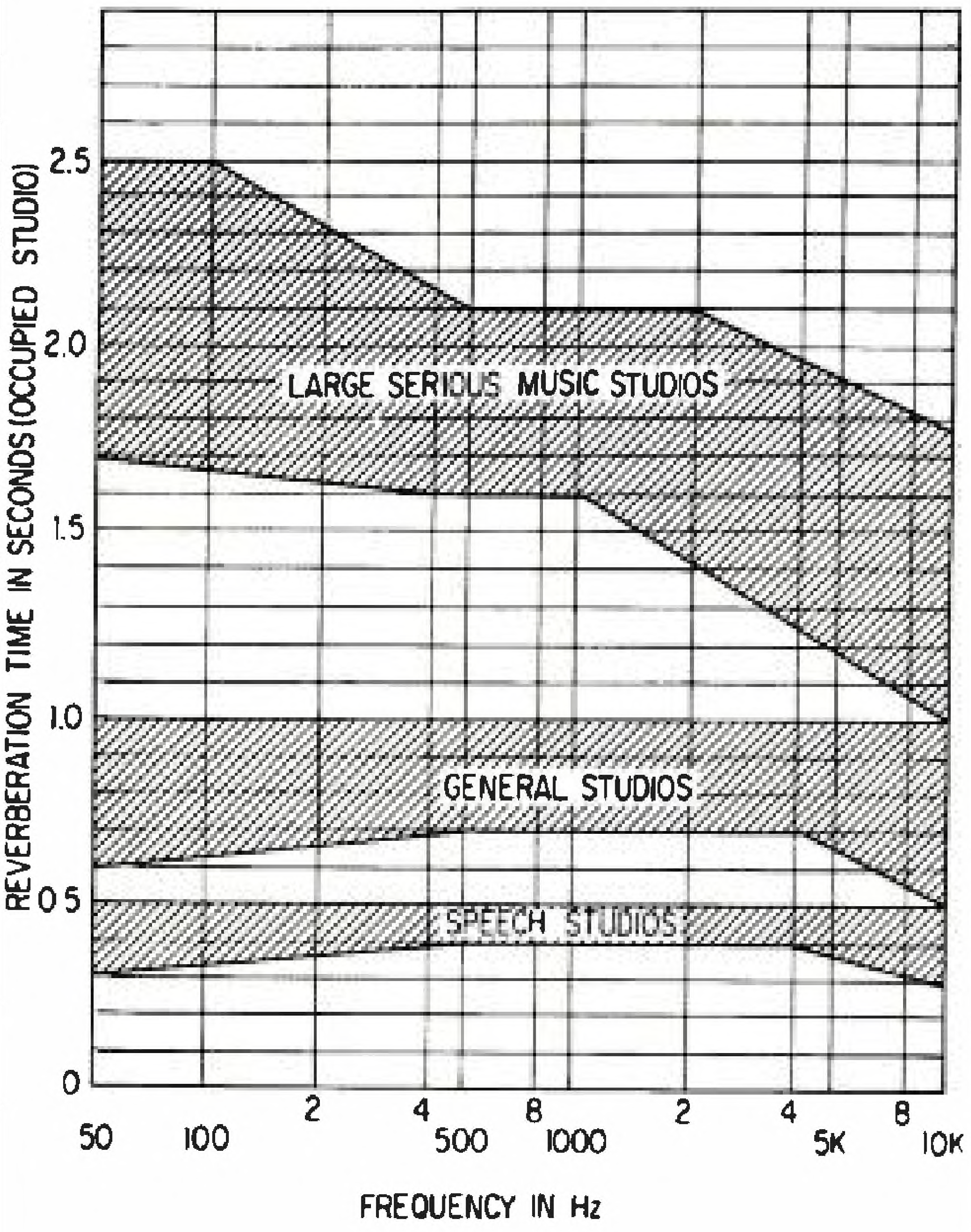

Figure 4. Suggested studio reverberation criteria.

1000 Hz and 1.6 seconds at 2000 Hz would be characterized as *warm*. On the other hand, a similar hall with reverberation times of 1.5 seconds, 2.0 seconds, and 2.0 seconds at 125, 500-1000, and 2000 Hz, respectively, would probably be characterized as *harsh*, or *bright*. Today, acoustical engineers plan large halls or studios for music performance to have rising low-frequency reverberation time characteristics: that is longer reverberation times at low frequencies than at middle or high frequencies.

In a speech studio, particularly a small one, a longer reverberation time characteristic at low frequencies would be characterized as a *boomy* acoustical environment. Speech-acoustics spaces should generally have flat reverberation time characteristics. Studios and auditoriums planned for both speech and music may be planned as a compromise, or — as discussed earlier — adjustable treatment or electronics may be employed to bridge the gap between optimum speech and optimum music conditions.

Initial Time Delay Gap and Ratio of Early-to-Reverberant Sound

These quantities have been analyzed primarily with respect to concert hall acoustics — although there is every indication that we should consider them important in large speech halls also.

In a large concert hall having an "ideal" reverberation time characteristic (a long one, say 2.0 seconds) there can be a tendency for the sound heard by a live audience to be *muddy* or lack sufficient clarity, particularly for classic (Mozart — Haydn) and contemporary (Stravinsky) music. Rather than shorten the reverberation time to obtain the added clarity, today's acoustical engineer would rather supplement the direct sound with additional sound energy that arrives at the listeners' ears soon enough to reinforce the direct sound, adding to clarity without destroying the richness of a long reverberation time. The goal is a "have your cake and eat it too" solution, which combines clarity and reverberation. Such a hall can have a large-hall liveness of sound with a small-hall intimacy. The time of arrival of these early reflections and their strength is important. If too late (after the initial sound) or too low in strength, they will be ineffective in aiding clarity: if they are too strong — and early enough — they will so dominate the sound heard by listeners that the liveness of the hall simply will not be heard, and the hall will have a reputation for *dryness* despite an adequately long reverberation time.

These early reflections may be compared to a pinch of pepper in a well-prepared soup. Just the right amount is needed. Too much and we'll taste only the pepper (too *much* clarity); not enough and the pepper may as well be absent (too *little* clarity); and the pepper should be added at the right time for best effect (the proper initial time delay gap).

The amount of energy in the early reflections, together with the energy of the direct sound, determines the ratio of early-to-reverberant sound, while the timing determines the "initial time delay gap". The ratio of early-to-reverberant sound is, for our purposes, defined as the ratio of sound energy received at a listener's position for the first 50 milliseconds during and after the receipt of the initial pulse of sound to the total sound energy received after the first 50 milliseconds.[3] Often, the inverse ratio — the ratio of rever-

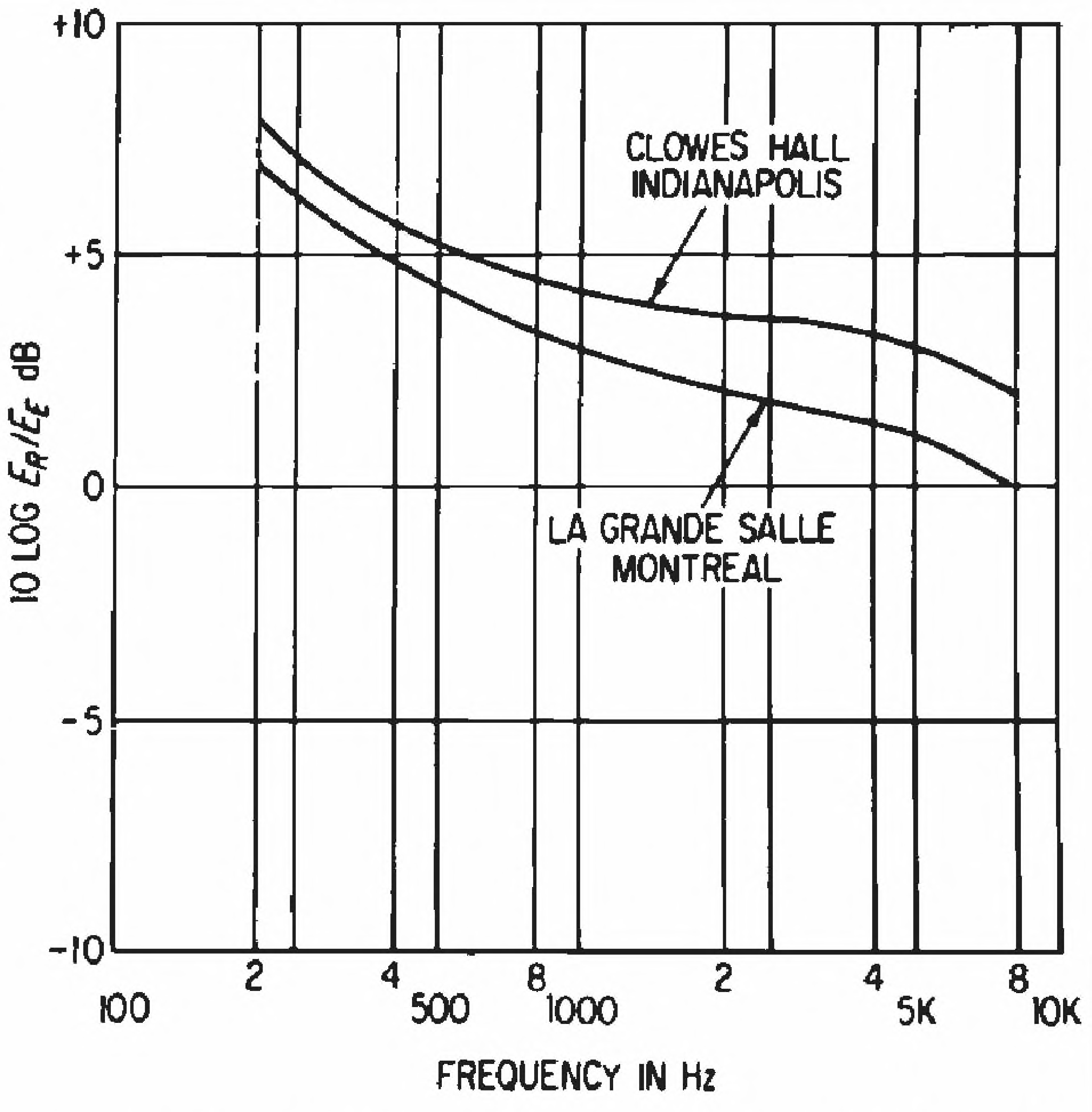

Figure 5. Ratio of reverberant sound energy to early sound energy of modern halls, expressed in dB (10 $\log_{10}$) as a function of frequency.

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[3] We assume use of a short-duration (5 milliseconds or less) pulse or impulsive sound source to obtain measurements of the quantities here discussed. Such sound sources would be analogous to transient sound in speech and music — the attack of a musical instrument or consonants in speech — rather than the stead-state or vowel sounds. Proper hearing of transients is necessary for adequate clarity.

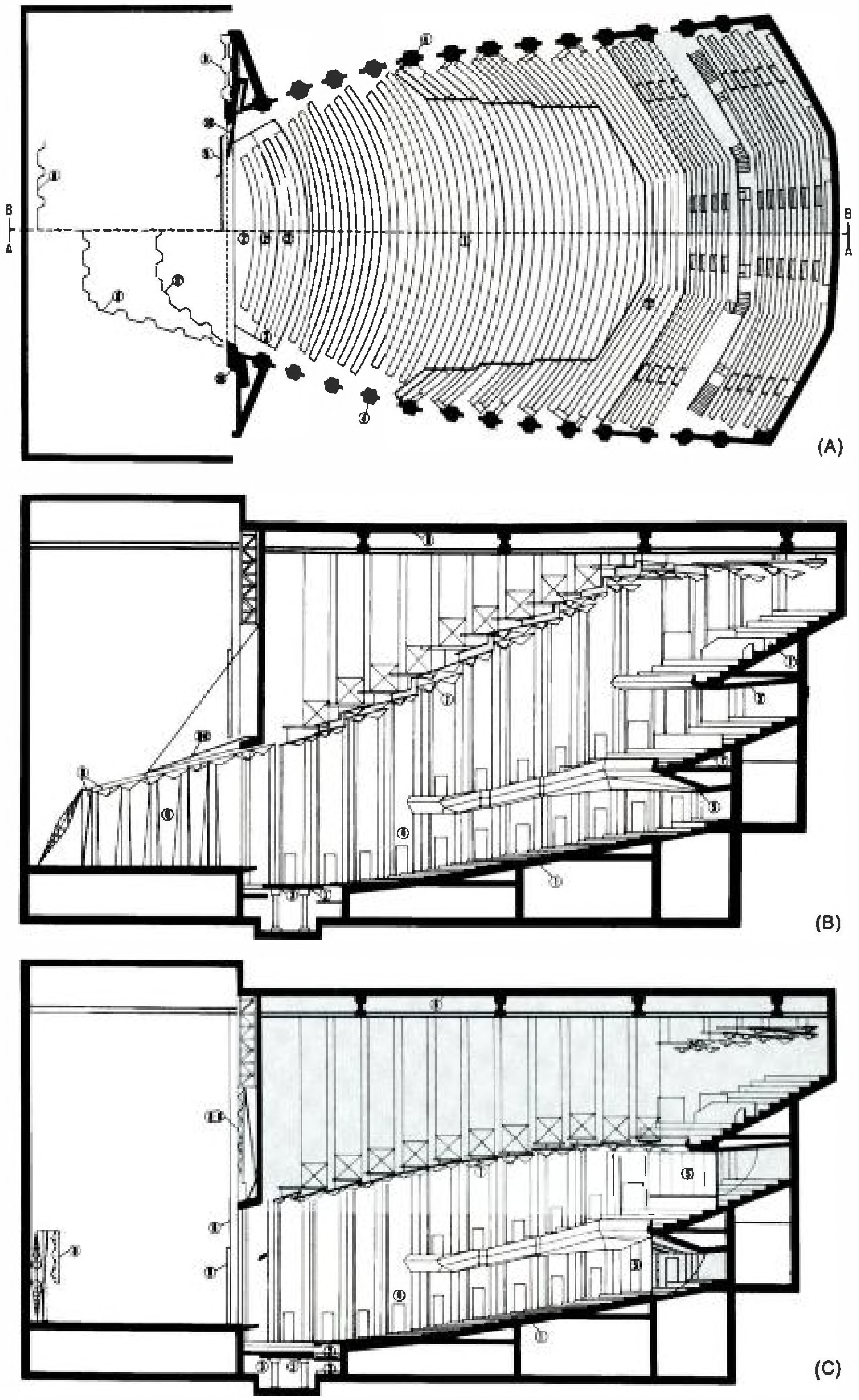

Figure 6. A 3000-seat Concert Hall-Opera House and 1700-seat Recital Hall-Theatre Combined in One Hall. (A)—Plan—left stage enclosure in position for 3000-seat concert hall, right, 1700-seat theatre, stage enclosure stored. (B)—Longitudinal section, stage enclosure in position for 3000-seat concert hall. (C)—Longitudinal section, stage enclosure stored for 1700-seat theatre.

1—Fixed Orchestra Seats 1′—Fixed Balcony Seats 2 and 2′—Movable Orchestra Seats 3 and 3′—Stage Apron Elevator 4—Fixed Auditorium Walls 5 and 5′—Sound-Transparent Movable Auditorium Walls 6—Fixed Auditorium Ceiling 7—Movable Auditorium Ceiling 8—Movable Stage Enclosure, Walls and Ceiling 8′—Movable Stage Enclosure Walls, Recital Position 9—Stage Teaser and Tormenter 10—Proscenium Pull-out Panels

Shaded areas are spaces closed off by movable ceiling and rear walls.

berant-to-early sound energy is used. The ratios are usually expressed in decibels rather than fractions. FIGURE 5 shows the ratios for two modern halls as a function of frequency.

The initial time delay gap is the delay between receipt of the initial sound and the receipt of the first reflection. Beranek's study (see Ref. 4) has indicated 0 to 20 milliseconds as ideal for the initial time delay gap, and up to 30 milliseconds as good.

The proper early-to-reverberant sound ratio and the initial time delay gap were inherent in the design of the older, narrow, rectangular "shoe box" concert halls. The designs included broken-up or diffuse side walls, spaced sufficiently close together (and to the halls' center-lines) to provide the required early reflections. However, the newer, larger and sometimes more radically shaped wide halls seem to require supplementary sound-reflecting *clouds* (Tanglewood; Clowes Hall in Indianapolis; Jones Hall in Houston; La Grand Salle, Place des Arts, Montreal; DeDolan Hall, Rotterdam; for example) or one large sound reflector per hall in the form of a "lip" (Saratoga Springs; Chandler Pavillion, Los Angeles; Opera House, Seattle) to assure the right balance between clarity and liveness.

The recording engineer may not be overly concerned with these balances. Given a sufficiently live hall, he can increase clarity by closer microphoning or use of more directional microphones; or increase liveness by use of more omnidirectional microphones or greater distance from source to microphones.

The sound-system designer may broaden his understanding of room acoustics problems to have a better grasp of the combined room-sound system results. In special cases, where architectural means are impractical, an electronic sound reinforcement system may be called upon to simulate early reflections by amplified sound.

Stage Enclosures

Auditoriums used for opera and plays usually have generous fly-space over the stage and side-stage areas to permit movement of scenery and curtains. These voids can act as traps for sound energy during live music performances; the proscenium (stage opening) acts as a barrier between the musicians on the stage and the audience. A music studio or concert hall surrounds an orchestra with many hard, sound-reflecting surfaces. Movable stage enclosures accomplish the same results in multi-purpose auditoriums, they help in the "quick-change act" between theater and concert hall. When in place, the enclosure assures that the audience and performers are in the "same room".

To be fully efficient, such enclosures should usually be constructed of fairly heavy material, usually weighing 2 lbs./sq. ft. or more, to reflect low-frequency sound energy which can pass through thin, lightweight material. Half-inch or three-quarter-inch plywood is a popular material for stage enclosures, both custom-built for particular halls and available from stock from several manufacturers.

Good critical reviews have greeted concerts performed within relatively lightweight enclosures. These enclosures employ a process which has been described as *selective absorption* to achieve optimum frequency response and instrumental balance. Gaps are left in certain areas of the enclosure to absorb middle and high-frequency energy, balancing the absorption of bass energy by thinner than usual material.

The usual system for the erection of a movable stage enclosure is for the ceiling pieces to be suspended on the theatrical rigging system, with the walls in the form of interlocking self-supporting pieces or rolling towers. There is a trend, however, to mechanized stage enclosures that reduce dependence upon normal stage-hand labor for erection and striking while freeing the rigging system completely for its prime purpose of storing scenery. In the Jesse H. Jones Hall for the Performing Arts, Houston, Texas, the forward ceiling panels of the stage enclosure fold down as one unit from the stage house wall above the proscenium, the side-walls fold out from the stagehouse walls on each side of the stagehouse, and the rear wall and rear ceiling fold out from the lower up-stage (rear stagehouse) walls. All this is accomplished with the help of push-buttons and electric motors. Such a theater design can free the acoustical designer toward the use of adequately heavy materials, regardless of their weight. In this case, 12 gauge steel, backed with damping material and faced with thin wood veneer was employed. The surface weight of the combined structure is close to 7 lb./sq. ft., assuring good sound reflection down to 25 Hz.

The improvement of an existing mutlipurpose theater-concert hall by provision of a properly designed stage enclosure, whether wood, plastic, or damped metal, is a familiar event today. Often the improvement in hearing conditions for the live audience is matched by improvements in liveness and balance in the sound as picked up by microphones; however, more often than not complete re-engineering of the microphone pickup arrangements are required if best results are to be obtained.

This article discusses the room acoustics aspects of studio, auditorium, and concert hall design. Future articles will touch on sound systems design, noise control, and sound isolation, all important parts of the over-all architectural acoustics picture.

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