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ARCHITECTURAL ACOUSTICS

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ARCHITECTURAL ACOUSTICS[1]

ABSTRACT

The fundamental principles governing the construction of an acoustically successful auditorium are no longer new, but are not yet generally understood by those engaged in such work. In this circular these principles are stated and an example is worked out showing their practical application to the planning of a new auditorium or to the curative treatment of one that has proved to be unsatisfactory.

CONTENTS

I. HISTORICAL ORIGIN

The scientific study of architectural acoustics is a thing of comparatively recent years. In 1895 Harvard University had just completed the Fogg Art Museum, containing an auditorium which proved almost unusable. The Corporation of the University appealed to the scientific staff of the faculty for advice and assistance in the matter, and Prof. W. C. Sabine undertook the study of the case. Two years were spent in the investigation of the questions involved, in the course of which experiments were made in a number of existing and satisfactory auditoriums. As a result, certain fundamental but previously unrecognized principles became clear, which later enabled Professor Sabine to predetermine the acoustic design of the new Boston Symphony Hall (1).[2]

These investigations of Sabine were the pioneer scientific work in the subject. So completely and carefully were they carried out that subsequent workers have done but little in the way of extending the theoretical foundations of the subject, and have for the most part merely enlarged our knowledge of the acoustic properties of the various materials commonly used in building construction.

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[1] Prepared by Paul R. Heyl, senior physicist, in charge of Sound Laboratory, Bureau of Standards.

[2] The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

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II. USUAL DEFECTS OF AUDITORIUMS

The usual defects of auditoriums are three—echo, dead spots, and reverberation. In the usual sense of the term, echo means a definite or articulate repetition of a sound after an interval at least equal to the total duration of the sound that is being repeated; while reverberation means a confused or inarticulate prolongation of the sound. Echo is always a bad feature in a hall; reverberation, on the other hand, is desirable up to a certain point; only in excess is it an evil. Of the two, echo is the more difficult to remove; prevention by foresight in construction, aided by expert advice, if necessary, is the best plan.

1. ECHO

Echo arises by regular reflection of sound from smooth walls, ceilings, or proscenium arches just as a mirror may reflect a beam of light without scattering it. If, however, the surface of the mirror be roughened the reflected light will be diffused in all directions; and if the walls and ceiling of a room be similarly irregular (on a sufficiently large scale) the reflected sound will be scattered, broken up, and its definite or articulate character destroyed. In this case we have what is called reverberation.

The lapse of time before an echo is heard is due to the fact that the reflected sound has traveled a longer path than the sound which comes directly from the source. This difference of path may be such as to cause much mischief. The reflected sound of a spoken syllable or of a note of music may arrive at the ear at the same moment as the succeeding syllable or note which has traveled by the direct path, and so cause hopeless confusion.

Generally speaking, auditoriums are less likely to exhibit troublesome echo when their outlines are rectangular. An instructive case of the trouble that may be caused by curved walls is cited by Watson (2) in the case of the auditorium at the University of Illinois, with an approximately circular floor plan and a hemispherical dome. The best that could be done in the way of after correction of the acoustics of the room was only partly satisfactory. Watson regards the complete cure of such a room as hopeless without "surgical treatment"; that is, straightening the walls.

Smooth, hard-finished walls, such as the usual plastered type, are excellent regular reflectors of sound and are consequently likely to produce echo. It becomes of importance, therefore, to break up such surfaces so as to produce irregular distribution of the reflected sound. This is usually done by coffering in the case of ceilings. Examples of this may be seen in many theaters of modern construction. The ceiling and, perhaps, the proscenium arch are broken up into depressions about 4 feet square, containing a succession of steps totaling a depth of, perhaps, 8 or 10 inches. An irregular surface of this character breaks up the reflected sound and distributes it in such a way as to minimize echo, and, in fact, to convert it into reverberation. The dimensions which should be assigned to such coffering are not a matter of taste or accident. If the wave length of the incident sound is very large compared to the size of the irregularities it encounters there will be little dispersive effect produced; and if very small, the smooth spaces inside the coffering may act as regular reflectors. The size mentioned, 4 feet in diameter, is a compromise between the average wave length of the male and the female voice.

2. DEAD SPOTS AND SOUND FOCI

Dead spots and sound foci occur as a consequence of echo-producing conditions. Sound travels through the air as a wave of alternate compression and rarefaction, and if a reflected sound wave is retarded by the proper amount it may happen that the compression of the directly transmitted sound and the rarefaction of the reflected sound arrive at the ear at the same time, neutralizing each other's effect and producing a diminution in intensity. If the reflected sound is retarded a little more it may happen that two compressions coincide, producing an unusually loud sound. The most usual cause of such sound foci, however, is a curved wall or ceiling which concentrates the sound to a focus.

Since dead spots and sound foci arise from the same cause as echo their removal may be brought about by the same treatment. Some care and experience is necessary in order to locate the particular portion of the room which is responsible for the production of a dead spot. Often this can be found only by a cut-and-try experiment, as it is not possible to predict the path of reflected sound with the same accuracy as in the case of light. The reflecting portion once found must be treated in such a way as to decrease its power of regular reflection.

W. C. Sabine mentions a case of a theater, the ceiling of which contained a flat oval panel, to which such trouble was traced. In this case an irregular canopy, oval in plan and slightly larger than the panel, was hung just below it with good effect.

3. REVERBERATION

A sound produced in a room is reflected back and forth from walls, floor, and ceiling, a portion being absorbed at each reflection until its intensity is so reduced that it becomes inaudible. Owing to the high speed of sound there may be many such reflections in the course of a single second in a room of ordinary size; and the greater the dimensions of the hall the more prolonged will be the reverberation.

If the walls of the room are covered with some highly sound-absorbent material, such as hair felt, two or three reflections may suffice to destroy the sound. Such a room is acoustically "dead" and undesirable. A little reverberation is necessary to satisfy our established tastes and auditory habit, and the desired amount of reverberation is found empirically to increase with the size of the auditorium.

It is customary since the pioneer work of Sabine to define the "reverberation time" of a room (perhaps, somewhat arbitrarily and artificially) as the time taken for a sound of specified intensity to die away to inaudibility. This standard intensity is a sound ordinarily painful to a normal ear at close range and is difficult of reproduction. Fortunately, its use is not necessary in ordinary practice, for since Sabine's day the "reverberation time" of a room is a matter of calculation rather than experiment. The method of making this calculation will be explained later.

Experience with a number of existing auditoriums of acceptable acoustic quality makes possible the formulation of the following table, in which the acceptable limits of the standard reverberation time are expressed for rooms of different volume.

TABLE 1

Volume of room in cubic feet	Acceptable limits of reverberation time in seconds		Volume of room in cubic feet	Acceptable limits of reverberation time in seconds	
	Half audience	Maximum audience		Half audience	Maximum audience
10,000	0.9–1.2	0.6–0.8	400,000	2.1–2.3	1.7–2.0
25,000	1.0–1.3	.8–1.1	600,000	2.3–2.6	1.8–2.2
50,000	1.2–1.5	.9–1.3	800,000	2.5–2.8	1.9–2.3
100,000	1.5–1.8	1.2–1.5	1,000,000	2.6–2.9	2.1–2.5
200,000	1.8–2.0	1.4–1.7			

The limits given in the table are not to be regarded as rigid. Auditoriums are known which exceed these limits in either direction by several tenths of a second and yet are of fairly satisfactory quality. However, in planning a new auditorium it should be the aim to strike the average of the range given.

III. CALCULATION OF THE REVERBERATION TIME

As a result of Professor Sabine's investigations we have a formula giving the reverberation time of a room. Let

t = reverberation time in seconds,

V = volume of room in cubic feet,

A = "total absorption" of the room (to be explained later).

Then the following relation holds:

$$t = \frac{0.05\, V}{A}$$

The only point that needs explanation in this formula is the quantity A.

Different materials differ considerably in their absorbing powers for sound. The most complete absorber known is an open window. It is theoretically possible that a small amount of sound may be sent back by diffraction from the edges of the window, but this quantity is so small that it is permissible to say that an open window is a perfect absorber. The next most perfect absorber of sound is probably hair felt, which may absorb, perhaps, half as much sound as an equal area of open window. In other words, if it may be said that an open window absorbs (or transmits) all the sound that falls upon it, its coefficient of absorption is unity, while that of the sample of hair felt quoted would be 0.50.

In like manner, every substance may be said to have its own absorption coefficient. This constant was measured by Sabine for a number of common materials, and later workers have extended the list.

Table 2 gives the absorption coefficients for a number of substances. Strictly speaking, these coefficients will vary somewhat with the frequency of the incident sound, and in Table 2 the values given are for a frequency of 512 (Watson).

In Table 3 there are given values of the total absorption of individual objects, and in Table 4 absorption coefficients of various substances for different sound frequencies, as determined at the Bureau of Standards.

TABLE 2.—*Sound absorption coefficients*

Akoustolith (artificial stone)	0. 36
Brick wall, 18 inches thick	. 032
Brick wall, painted	. 017
Brick, set in Portland cement	. 025
Carpets, unlined	. 15
Carpets, lined	. 20
Carpets, heavy, with lining	. 25
Carpet rugs	. 20
Celotex, one-half inch thick	. 31
Cheesecloth	. 019
Cocoa matting, lined	. 17
Concrete	. 015
Cork tile	. 03
Cretonne cloth	. 15
Curtains, chenille	. 23
Curtains, in heavy folds	0. 5 to 1. 0
Flax, 1 inch thick, with unpainted membrane	. 55
Glass, single thickness	. 027
Hair felt, 1 inch thick, with unpainted membrane	. 55
Hair felt, 1 inch thick, with painted membrane	. 25 to . 45
Hair felt, 2 inches thick, with unpainted membrane	. 70
Hair felt, 2 inches thick, with painted membrane	. 40 to . 60
Insulite, one-half inch thick	. 31
Linoleum	. 03

TABLE 2—*Sound absorption coefficients*—Continued

Marble		0.01
Oil paintings, including frames		.28
Open window		1.00
Oriental rugs, extra heavy		.29
Plaster on wood lath		.034
Plaster on wire lath		.033
Plaster on tile		.025
Stage opening, depending on stage furnishing	.25 to	.40
Varnished wood		.03
Ventilators (50 per cent open space)		.50
Wood sheathing		.061
Wood, varnished		.03

TABLE 3.—*Total absorption by individual objects*

Audience	per person		4.7
Church pews	per seat		.2
House plants	per cubic foot		.0031
Seats, upholstered, depending on material and lining	per seat	1.0 to	2.5
Seat cushions, cotton, covered with corduroy	do		2.16
Seat cushions, hair covered with canvas and light damask	do		2.27
Settees, upholstered in hair and leather, seat and back	do		3
Wood seats, for auditoriums	do		.100

TABLE 4.—*Absorption coefficients*

Material	297	581	1,095	2,190	2,890
Glass	0.021		0.020	0.010	
⅝-inch celotex	.058		.056	.072	0.097
Celotex B	.178		.399	.734	.708
Sound absorbing tile No. 1	.079		.116	.401	.35
Same No. 2	.078		.127	.201	.213
Hair felt, 1 inch	.330		.62	[1] .94	[1] .90
Brick	.019		.019	.056	.021
Pine wood	.012	0.009	.016	.016	.009
Oak wood	.011	.007	.011	.006	.005
Akoustolith		.301	.434	.380	.272
Brass	.021	.015	.023	.004	.001
½-inch insulite	.056	.102	.182	.256	.172
½-inch flax-li-num		.229	.312	.503	.336
1-inch flax-li-num	.182	.422	.456	.569	.407

[1] The absorption at 2,190 and at 2,890 cycles was measured upon a different piece of material from that used at 297 and at 1,095 cycles.

As an example of the use of these coefficients let us take an auditorium of 100,000 cubic feet capacity, including the stage opening. There is a floor laid with cork tile of an area of 4,550 square feet, a plastered ceiling (on wire lath) with the same area, 2,860 square feet of plastered walls, a stage opening of 600 square feet, and 500 plain wooden seats. The calculation of the total absorption of the empty room is made as follows:

Floor	4,550 × 0.03 =	[2] 137
Ceiling	4,550 × .033 =	152
Walls	2,860 × .033 =	95
Stage opening (no furnishing, bare walls)	600 × .25 =	150
Seats	500 × .1 =	50
Total absorption of empty room	=	584

[2] Nearest integer sufficient.

In the case of a half audience we must add $250 \times 4.7 = 1{,}175$ and subtract the absorption of 250 seats at 0.1, giving the net addition of 1,150 absorption units and bringing the total absorption up to 1,734. The reverberation time for half audience is then found by the formula

$$\frac{0.05 \times 100{,}000}{1{,}734} = 2.9 \text{ seconds,}$$

which is considerably too large, the acceptable range for this size of room being (by Table 1) 1.5 to 1.8 seconds for a half audience.

For full audience we add to the absorption of the empty room $500 \times 4.7 = 2{,}350$ and subtract $500 \times 0.1 = 50$, making a net addition of 2,300, giving for the total absorption of the room 2,884, with a reverberation time of 1.7, a little in excess of the upper limit of 1.5 in Table 1, but not seriously so. However, as a maximum audience can not always be relied upon, it is well to add absorbing material to the walls to reduce the reverberation time in the case of the half audience at least to the upper limit, 1.8 seconds.

This would require a total absorption given by the formula

$$A = \frac{0.05\,V}{t} = \frac{5{,}000}{1.8} = 2{,}777 \text{ absorption units.}$$

The value of A for half audience has been previously found to be 1,734; hence 1,043 units of additional absorption are required.

The choice of absorbing material is a question of price and appearance. Suppose it is decided to use a hypothetical material of coefficient 0.25. The coefficient of the plaster which this covers is 0.03, hence the net coefficient of added absorption is 0.22. To obtain a total absorption of 1,043 units would require the application of $\frac{1{,}043}{0.22} = 4{,}741$ square feet of material. This is slightly in excess of the ceiling area and much greater than the available wall space. The best practical solution would be to distribute the material as uniformly as possible, filling wall panels only (if such exist) and placing the remainder on the ceiling in some acceptable pattern which shall cover the whole ceiling.

Distributing the absorbing material in strips or patches has the added advantage of reducing somewhat any echo that may exist, as the reflected sound is thereby broken up.

The application of this absorbing material will reduce the reverberation time for full audience to

$$\frac{0.05 \times 100{,}000}{2{,}884 + 1{,}043} = 1.3 \text{ seconds}$$

within the allowable range, though near its lower limit.

IV. PLANNING AN AUDITORIUM

In planning an auditorium we must consider three factors—shape, size, and interior finish.

As stated in discussing echo, the design of an auditorium should avoid curved walls or ceilings. An attempt to introduce such features for their artistic effect is almost certain to be detrimental to the acoustic quality of the room. Auditoriums of a rectangular shape have been the most uniformly satisfactory.

Prior to Sabine's work there was current an idea that there should be a certain ratio existing in the dimensions of the room; just what ratio no one seemed to know certainly. Sabine quotes several different recommendations. Modern opinion regards such a ratio as immaterial unless, of course, it be carried to an absurd extreme, such as a very long and narrow room.

The question of size must be determined principally by the purpose for which the room is to be used and not by considerations of space available or seating capacity desired. True, modern amplifying practice makes it possible to use a very large auditorium for speaking, but the present discussion is limited to the consideration of natural features and characteristics. The alteration of quality and the noise introduced by amplifiers are such that they will require much improvement before they will be acceptable for the rendition of anything in which artistic quality is a prime requisite, and for this purpose unassisted auditoriums will for a long time, perhaps always, be the rule.

Generally speaking, a theater must be moderate in size, while an auditorium for musical numbers, such as orchestral or choral performances, may be much larger. Such performances usually include several vocal solo numbers and this rather limits the size of the room.

Experience with existing auditoriums leads to an empirical rule connecting the volume of the room with the maximum number of orchestral instruments suitable. This rule is expressed in Table 5. No distinction is here made between wind and string instruments, which are supposed to be present in balanced quantity.

In case the orchestra is reinforced by the organ due allowance must be made. The new music room at the Library of Congress is a case in point. Its volume is about 100,000 cubic feet. At the opening concert there was present an orchestra of 26 pieces, which, with the organ, produced an excessive reverberation perceptibly spoiling the effect of sudden pauses after a loud chord. The indicated limit for this room is, perhaps, 12 or 15 pieces with the organ.

As to interior finish, this should be planned with both echo and reverberation in mind. A liberal use of coffering on ceiling and sloping upper walls should effectually prevent echo from this source, and the interior finish should be calculated to give a reverberation time as indicated by the average range in Table 1, using panels of absorbing material in such quantity as may be necessary to reduce the reverberation time to a suitable value. Such materials, of several kinds, are now available commercially.

TABLE 5

Volume of room	Number of instruments
50,000	10
100,000	20
200,000	30
500,000	60
800,000	90

V. BIBLIOGRAPHY

1. Sabine, Collected Papers on Acoustics, Harvard University Press; 1922.
2. Watson, Acoustics of Buildings, John Wiley & Sons, New York; 1923.
3. Eckhardt, The Acoustics of Rooms, Jour. Franklin Inst.; June, 1923.
4. Swan, Architectural Acoustics, Jour. Am. Inst. Architects; December, 1919.

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