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Acoustical Criteria for Auditoriums and Their Relation to Model Techniques

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The first step in using model technique as a design tool is to establish a quantitative criterion (besides reverberation time). "Early to reverberant energy," "steepness," and "initial reverberation time" or "early decay time" (EDT) must be considered the most relevant factors, from aspects such as: (1) simplicity of measurement, (2) correlation with subjective assessments, and (3) possibility of comparing values obtained in scaled models with values obtained in full-size halls. Measured values of EDT may be applied either by calculating the inversion index, i.e., the average value in the audience area of a hall divided by the average value in the stage area, or by comparing values of EDT measured in different locations of a model (or a hall) with values of average reverberation time. These techniques have been applied in a number of 1:10 scale models and, also, in some completed halls.

INTRODUCTION

The problem of predicting the acoustical quality of a concert hall before the hall actually is built has occupied many acousticians. It is generally agreed that reverberation time (RT) is not sufficient as a criterion for acoustical quality, and many also agree that there is no such thing as a single optimal value of RT, but that, more likely, there is an optimal range that is less dependent on the volume of the hall than on the musical style of the performance. Evidence of this exists so far, however, only from the subjective assessments of monaural recordings.[1]

What else do we have? Two other concepts, "definition" and "diffusivity," have been advocated in recent years, followed by a number of other proposals. Most of them are related to the pattern of early reflections that follow the direct sound wave. A general theory for this pattern of early reflections apparently does not exist; nor, if we think in terms of sound energy, do we have such a theory for the first part of the decay curve. By the application of scaled models, these phenomena, however, can be studied in advance. If such model studies become generally useful, if, in fact, they become universally recognized as an indispensable part of the design of any large music hall project—then it seems necessary that an elementary approach be adopted with regard to the establishment of a single significant criterion (and the corresponding practical method of measurement).

This criterion should not replace RT but should, rather, constitute a refinement that also must be closely related to RT. Moreover, it should be possible to correlate numerical values of this criterion directly with subjective assessments. We comment briefly on some recent attempts to establish such a criterion.

I. EARLY ENERGY/REVERBERANT ENERGY

This concept is a development of the earlier German proposal of *Deutlichkeit* (definition as proposed by R. Thiele[2]). The energy from a short pulse or tone burst arriving within the first 50 msec after the direct sound, in proportion to the total energy, is called *Deutlichkeit* and is measured as a percentage figure. Later, Beranek and Schultz[3] used the reciprocal term (on a logarithmic basis: 10 $\log E_R/E_E$) to classify different concert halls and to establish accordance with subjective assessments, although no systematic investigation of probable correlation between criterion and assessment was undertaken. However, variations of reverberant to early energy under different conditions in one of the concert

[1] W. Kuhl, "Über Versuche zur Ermittlung der Günstigsten Nachhallzeit Grosser Musikstudios," Acustica 4, 618–634 (1954).

[2] R. Thiele, "Richtungsverteilung und Zeitfolge der Schallrückwürfe in Raümen," Acustica 3, 291–302 (1953).

[3] L. L. Beranek and T. J. Schultz, "Some Recent Experiences in the Design and Testing of Concert Halls with Suspended Panel Arrays," Acustica 15, 307–316 (1965).

TABLE I. Values of rise time and steepness of the Concert Studio, Copenhagen ($\sigma_{\text{calc}}=0.087$ dB/msec).

Source location (on platform)	Microphone location	With no reflectors Rise time (msec)	Steepness (dB/msec)	Reflectors above stage Rise time (msec)	Steepness (dB/msec)
left	platform right	70	0.023	48	0.063
center	platform rear	105	0.024	55	0.060
right	audience area (sixth row)	60	0.050	70	...
right	audience area (balcony—first row)	50	0.073	60	...

halls (Philharmonic Hall, Lincoln Center) were related to subjective assessments.

Later, Schroeder *et al.*[4] in a series of measurements under different conditions, also in Philharmonic Hall measured among various other quantities, the proportion of early energy to reverberant energy (the reciprocal of the expression used by Beranek and Schultz). Although some of the conditions were identical or in both cases the variations were not. A comparison of the results indicates that the different frequency ranges investigated in the two cases may explain this apparent discrepancy. Recently, W. Reichardt[5] has suggested a definite relationship between two physical parameters: (1) reverberation time, and (2) the quotient of direct energy over reverberant energy and the psychological term *Raümlichkeit* (room perception), for which a scale has been established in experiment. This method is suggested in association with an appraisal of secondary influences, including early lateral reflections, low-frequency content of the signal, and musical style.

II. STEEPNESS

This concept was introduced in connection with some experiments undertaken in a concert studio in Copenhagen. The experience in the concert studio over the years (since its completion in 1945) had been that the divergency in plan and the considerable ceiling height (especially over the stage area) produced hearing difficulties for the conductor and for different groups of the orchestra.[6] After some experimentation, it was found that the hearing problems were solved when horizontal reflectors were suspended over the orchestra platform. Measurements of rise time were later superseded by measurements of steepness, defined as:

$$\sigma_{(-5)}=|(d/dt)\{10\log[I_{(-5)}/I_0]\}| \quad \text{(in decibels/millisecond)},$$

where I_0 is the stationary intensity of a (long) noise pulse and $I_{(-5)}$ is the intensity at a level 5 dB below the stationary level. The expression therefore signifies the slope of the rise curve of a (long) pulse at a point 5 dB below the stationary level. Originally, these measurements were made on many repeated (long) noise pulses, but later this method was superseded by the pulse-integrating method of Schroeder,[7] the only difference being that the rise curve, not the decay curve, was used.

Table I shows some of the results from the concert studio in Copenhagen. It was adopted as a basis for the more general judgment that values of steepness in general ought to be higher close to the sound source rather than farther away. In accordance with this idea, the concept of an inversion index was introduced. This index was defined as the ratio of average steepness in the stage area to the average steepness in the audience area. Theoretically, values of steepness can be calculated from a simple formula (that assumes complete diffuse conditions and, also, complementarity of rise and decay curves). If the rise curve follows the function

$$I=I_0(1-e^{-kt}),$$

then the slope of the curve is (numerically)

$$\begin{aligned}|(d/dt)[10\log(I/I_0)]| &= 10\ln[ke^{-kt}/(1-e^{-kt})] \quad \text{(in decibels/millisecond)}\\ &= 10^{-2}\ln[ke^{-kt}/(1-e^{-kt})] \quad \text{(in decibels/millisecond)}.\end{aligned}$$

By inserting the values corresponding to the −5-dB-point of the rise curve, one gets:

$$I_{(-5)}=0.13/T, \quad \text{(in decibels/millisecond)},$$

where T, the reverberation time, should be expressed in seconds.

III. EARLY-DECAY TIME

Theoretically, it has been shown[8] that we can expect complementarity between rise and decay curves of integrated (short) pulses. Consequently, we can also expect that the phenomenon of inversion can be predicted by measuring initial reverberation time (instead of steepness). Initial reverberation time was defined by Atal, Schroeder, and Sessler[9] as the RT corresponding either

[4] M. R. Schroeder, B. S. Atal, G. M. Sessler, and J. E. West, "Acoustical Measurements in Philharmonic Hall (New York)," J. Acoust. Soc. Amer. 40, 434–440, 1966.

[5] W. Reichardt, "Der Impuls-Schalltest und seine Raumakustische Beurteilung," Int. Congr. Acoust., 6th, Tokyo, General Prog. Papers GP 11–GP 20 (1968).

[6] V. L. Jordan, "The Building-up Process of Sound Pulses in a Room and Its Relation to Concert Hall Quality," Proc. Int. Congr. Acoust., 3rd, 2, 922–925 (1959).

[7] M. R. Schroeder, "New Method of Measuring Reverberation Time," J. Acoust. Soc. Amer. 37, 409 412, 1965.

[8] M. R. Schroeder, "Complementarity of Sound Buildup and Decay," J. Acoust. Soc. Amer. 40, 549–551 (1966).

[9] B. S. Atal, M. R. Schroeder, and G. M. Sessler, "Subjective Reverberation Time and Its Relation to Sound Decay," Int. Congr. Acoust., 5th, Liège (1965), Vol. Ib, Paper G32.

to the first 160 msec of the decay or to the first 15 dB of the decay. This was done in conjunction with their experiments on the correlation between this value and subjective reverberation time. However, in the following discussion we have preferred to rename this concept and call it early decay time (EDT), since the interval actually used by us differs from either of the above definitions. Early decay time is defined as the RT corresponding to the slope measured over the first 10 dB of the decay.

Having measured values of EDT over the stage area and over the audience area of a hall, we may again introduce the concept of inversion index. Considering the complementarity of rise and decay curves, this index is now defined as the ratio of the average EDT in the audience area to the average EDT on stage. Experience with measurements of early decay time seems to confirm that a critical value is obtained when the first 10 dB of the decay curve are used. The value seems to be particularly sensitive to changes in the general shape of a hall. This interesting fact should be considered in connection with the high degree of correlation already found experimentally between initial reverberation time and subjective reverberation[9] (at least for artificially reverberated signals).

IV. COMPARISON OF THE DIFFERENT CRITERIA

When comparing the three different criteria mentioned, it does not seem unfair to conclude that:

(1) EDT is the easiest to measure and requires the least sophisticated instrumentation. As sound source, either tone bursts or electric-spark sources can be used in models, whereas tone bursts, gun shots, or balloon bursts can be used in full-size halls. It is convenient, when investigating models, to use tape recorders, since this makes direct listening to signals (at reduced speed) possible. The subsequent reversing of the tape is also the easiest way of handling the pulse integration.

(2) EDT so far has the best-established correlation with subjective assessments.

(3) EDT measurements in models (e.g., 1:10 models) and in the corresponding halls show comparable results when the following precautions are taken: (a) point sources and point receivers are essential (a $\frac{1}{4}$-in. condenser microphone is satisfactory when working with models of 1:10 scale); (b) all recording locations must be situated in the area where the reverberant field is predominant; (c) reflecting surfaces of the model must have the same order of absorption coefficient at model frequencies as corresponding surfaces of the hall; (d) absorption (and preferably also diffusion) of the audience must be simulated in the model[10]; (e) the frequency range of measurements should be restricted to the range where the amount of sound absorption of the air in proportion to the total absorption is not too different from conditions existing in full-scale halls. This means, for example, when 1:10 scale models are used, that octave bands higher than 16 kHz should not be included.

V. INTERPRETATION OF EDT MEASUREMENTS

Since we have postulated that measuring values of EDT (on 1:10 scale models) is a practical method of approaching design problems of large halls, the important question becomes: How do we interpret the values measured? Of the two different ways in which this is done, one has already been indicated:

(1) By averaging the values measured on the orchestra platform and the values measured in the audience area, we can calculate the inversion index. It seems obvious that in any concert hall the conditions should not be such that a state of diffusion is reached earlier in the audience area than in the stage area. This, however, sometimes is the case in existing halls. The type of hall where many early reflections are directed towards the audience (and very few towards the orchestra) is likely to have larger values of steepness (smaller values of EDT) in the audience area than in the stage area, i.e., to have an inversion index smaller than 1.0. In contrast, the more classical type of concert hall, with a general shape not too far from the rectangular shape, tends to diffuse much of the sound energy already in the stage area (and maybe also in the volume above the audience). In such a hall it is likely that the inversion index will be 1.0 or even higher. The early decay in this type of hall is not just the beginning of a general reverberation process but, rather, the result of a diffused sound field being radiated towards the audience. An over-all judgment of a concert hall thus seems to involve the experimental finding of its particular value of inversion index and, in case of new designs, this value measured on a model.

(2) Individual locations in a concert hall or an opera theater can be judged according to measured values of EDT compared with measured values of average RT (with an interval of −5 to −35 dB). This is done under the assumption that values of EDT should be close to values of average RT. Values of EDT larger than values of RT may signify favorable conditions, especially for a hall where the value of RT is on the low side.

VI. MEASUREMENTS IN HALLS AND MODELS

A. New York State Theater, Lincoln Center

The results obtained on a 1:10 scale model and in the auditorium proper have been reported elsewhere.[11] Values of steepness were at that time given in reciprocal units (in milliseconds/decibel). Some of the results, converted to current form, are repeated in Table II.

[10] B. F. Day, "A Tenth Scale Model Audience," Appl. Acoust. 1, 121–135 (1968).

[11] V. L. Jordan, "Acoustical Considerations Concerning New York State Theater," J. Audio Eng. Soc. 13, 98–103 (1965).

TABLE II. Values of the steepness of the New York State Theater, Lincoln Center.

Microphone location (sound source at the proscenium)	Steepness in dB/msec Model (1:10) 16-kHz octave	Auditorium 1600-Hz octave
Audience area		
Orchestra, center	0.54	0.062
Orchestra, rear	0.82	0.086
Orchestra, left side	1.00	0.106
Orchestra, center right	0.73	0.087
Fourth Balcony, center	0.67	0.067
Average	0.75	0.082
σ_{calc}	0.81	0.081

B. Metropolitan Opera House, Lincoln Center

A 1:10 scale model was used for measurements of steepness and EDT. The values of steepness show reasonably good agreement.[12] Values of EDT are close to values of average RT, and this was found by both measurements in the model and in the hall. Some of the results are shown in Table III. Values in the model are somewhat below the one-tenth value of RT in the auditorium, which was measured while empty.

At one occasion, the auditorium was measured occupied (occupancy: about 3000 school children) by firing gunshots at the proscenium. The recorded tapes were analyzed in $\frac{1}{3}$-oct bands. The results are shown on Fig. 1, which, for comparison, shows values measured in the old Metropolitan Opera[13]: there is a marked difference, especially at the higher frequencies.

The same tapes were also analyzed in octave bands, and the values of average reverberation time are shown on Fig. 2. For unknown reasons, these values are 10%–20% higher than the values obtained through $\frac{1}{3}$-oct bands. Figure 2 also shows measured values of EDT (from the same tapes) in octave bands. These values are close to the average reverberation time values, in most cases. Figure 3 shows the octave values of EDT and RT in the empty auditorium. At low frequencies, the EDT values are somewhat smaller than the average RT values. In the author's opinion, there are three main factors of importance for the apparently very satisfactory results of this design: (1) the value of average RT, which is rather high and approximately constant up to 2000 Hz; (2) values of EDT, mostly very close to values of RT; (3) the shape of the proscenium (shown in Fig. 4) has a deep frame, favoring early side reflections. (The last two factors may actually be interrelated.)

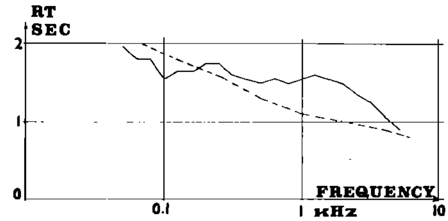

FIG. 1. Reverberation time versus frequency (0.1–10 kHz). *Solid line:* measured in $\frac{1}{3}$-oct values in the occupied auditorium of the Metropolitan Opera, Lincoln Center. *Dotted line:* measured in the Old Metropolitan Opera (Bolt Beranek and Newman, see Ref. 13).

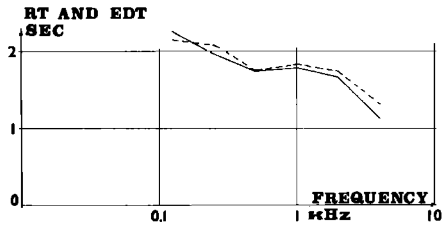

FIG. 2. RT and EDT versus frequency (0.1–10 kHz). *Solid line:* RT measured in octave values in the occupied auditorium of the Metropolitan Opera, Lincoln Center. *Dotted line:* EDT measured in octave values under the same conditions.

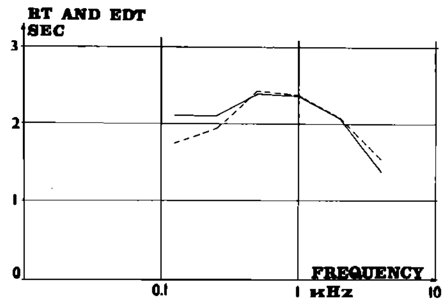

FIG. 3. RT and EDT versus frequency (0.1–10 kHz). *Solid line:* RT measured in octave values in the unoccupied auditorium of the Metropolitan Opera, Lincoln Center. *Dotted line:* EDT measured in octave values under the same conditions.

C. Oslo Concert Hall (Model)

Preliminary results of various ceiling shapes from a model test in a 1:10 scale model have been reported elsewhere.[14,15] The hall is not yet completed.

D. Reykjavik Concert Hall (Auditorium)

This hall was completed in 1962. There were some complaints, especially with regard to the acoustics of the platform area. Figure 5 shows the plan and longitudinal section of the hall. Originally, the intended side screens were not put in, so a heavy plastic curtain was the only surface giving side reflections.

[12] V. L. Jordan, "Room Acoustics and Architectural Acoustics, Development in Recent Years," Appl. Acoust. 2, 59–81, (1969).

[13] L. L. Beranek, *Music, Acoustics and Architecture*, (John Wiley & Sons, Inc., New York, 1962), Table A2, IIb, p. 564.

[14] V. L. Jordan, "Einige Bemerkungen über Anhall und Anfangsnachhall in Musikraümen," Appl. Acoust. 1, 29–36 (1968).

[15] V. L. Jordan, "Errata," Appl. Acoust. 1, 152 (1968).

TABLE III. Values of reverberation time and early decay time of the Metropolitan Opera House, Lincoln Center.

Microphone location (sound source at the proscenium)	Frequency range (model values divided by 10)	Model (values multiplied by 10) RT(sec)	Model (values multiplied by 10) EDT(sec)	Auditorium, empty RT(sec)	Auditorium, empty EDT(sec)
Orchestra seating, center	oct at 1000 Hz	1.64	1.63	2.27	2.15
Orchestra seating, center	$\frac{1}{3}$ oct at 1600 Hz	1.41	1.44	...	...
Average of five orchestra locations	$\frac{1}{3}$ oct at 1600 Hz	...	...	2.19	2.11
Average of five orchestra locations	oct at 2000 Hz	...	...	1.87	1.83
Average of seven locations (orchestra and balconies)	oct at 2000 Hz	1.41	1.53	...	...

Later, side screens were added, and the draped curtain was straightened out. Measurements of RT and EDT were taken before and after this operation. Results are shown on Figs. 6 and 7. The increase in values of EDT, especially in the medium-frequency range, is considerable. This means that values of EDT now are very close to values of RT. The preliminary reactions from the musicians indicate an improvement of the conditions in the platform area.

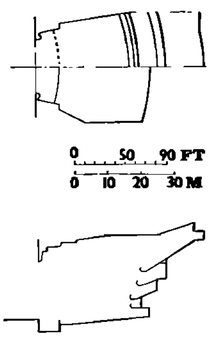

FIG. 4. Schematic plans and long section of the Metropolitan Opera House, Lincoln Center.

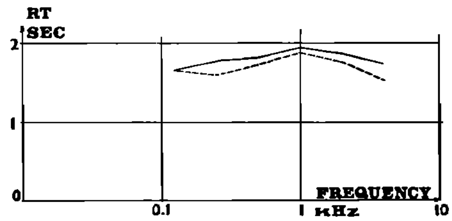

FIG. 6. RT versus frequency (0.1–10 kHz) in Reykjavik Concert Hall. *Solid line:* after alterations. *Dotted line:* before alterations.

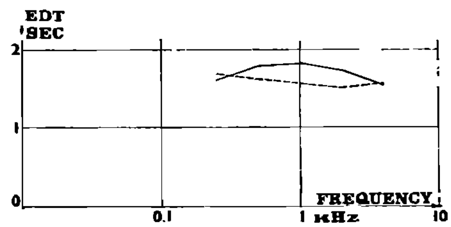

FIG. 7. EDT versus frequency (0.1–10 kHz) in Reykjavik Concert Hall. *Solid line:* after alterations. *Dotted line:* before alterations.

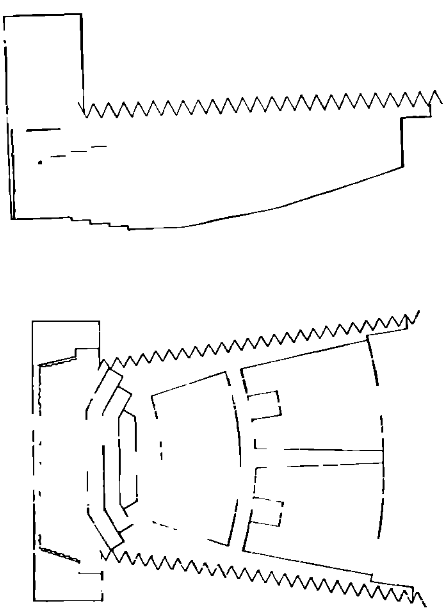

FIG. 5. Plan and long section of Reykjavik Concert Hall.

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