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AUDITORIUM ACOUSTICS, (CRITERIA, EXAMPLES, TRENDS)

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(1) Introduction

The subject of this lecture cannot be condensed into a normal lecture period so it may be more appropriate to concentrate on certain aspects of auditorium acoustics.

In recent years there has been devoted much time and interest to the development of adequate design criteria and this would therefore be the first aspect to approach. Following that it might be worth while to review a number of examples of completed auditoria and the experience gained from their practical use (included will also be a few projects of halls not yet built).

In conclusion, then, it would be natural to indicate some important trends in current and future design of auditoria.

(2) Criteria for Speech and Music

For speech the well established criteria: level of sound and articulation are the obvious points of departure.

Even in rather large auditoria many speakers will find that their natural speech power will be sufficient to produce the necessary sound level for the whole audience. The articulation, however, will depend upon the acoustical properties of the auditorium traditionally determined by the statistical value (or the Sabine value) of reverberation time (abridged: RT). Already many years ago it was established that a better objective criterion than RT was the so called definition (German: Deutlichkeit). Definition may be measured by using the impulse method, by which very short pulses (random noise or shots) are radiated in an auditorium. The sound pulses are picked up by microphone, recorded and analyzed. The energy arriving within the first 50 millisec. is compared with the total energy of a pulse and the ratio is called definition. It has been shown that articulation or intelligibility as measured according to the syllable method is very close correlated with numerical values of definition.

Originally, for music, the generally acknowledged criterion was reverberation time (RT) and adopted values were in an uncertain range between 1 and 2.5 sec. (depending upon size of music room and no. of musicians). For full size concert halls an adequate value around 2 sec has for some years been a sort of stand - ard.

However, during the last 10-20 years, experimental work with the so called short time criteria has established that RT is not a critical value for subjective assessments but that the following criteria must be considered by the design of concert halls:

Early Decay Time (EDT) defined by the slope of the first 10 dB of a reverberation process. It has been shown that only this part of the reverberation is evaluated by listening to music. Subjectively, we may speak of EDT as a measure of reverberance.

Clarity (C) is a parameter corresponding to definition for speech. The "transparency" of music (whether in time succession or in tonal balance) demands that rapid passages must not be blurred. Clarity is defined (using short pulses) as 10 times the logarithm of the ratio of energy within the first 80 millisec. to the remaining energy.

Tolerance limits for EDT have been established as covering the interval 1.8 - 2.6 sec. whereas tolerance limits for Clarity are somewhat more loosely defined. An interval of $\pm$ 2 dB may be too rigid.

A problem has occurred in correlation experiments (where objective criteria are compared with subjective assessments): that the musical judges may end up being divided into groups. One group may have favored relatively large values of EDT and correspondingly low values of C and another group may have preferred the opposite.

The level of the music (as actually being performed in a concert hall) is also a criterion and there have been indications, that f.i. the level of a mezzo forte passage could divide the assessors into two groups, each with its individual preference of level, although the actual difference between optimum preferences (the two groups average values) was only 4 dB (84 dB(A) and 88 dB(A)) for mezzo forte.

The optimal, spectral balance of the music may be regarded as a not finally solved problem.

Originally, when RT was used as a general criterion the RT vs. frequency characteristic (octave or one third octave values) was thought of as the basis for assessments of tonal balance. Many acousticians have emphasized the importance of an increase in RT value towards the lower frequencies, others (among them the author) have considered this of little consequence. A slight increase of RT value towards the higher frequencies, however, may be regarded as more important.

Recently the EDT vs. frequency has been used as the objective measure for spectral balance.

So far, we have only considered criteria which do not distinguish between the different directions from which the sound reaches the listener. There is a strong evidence that among the early reflections it is particularly lateral reflections which are valuable, since they contribute both to the clarity and to the spatial impression.

It seems necessary to distinguish between "Spatial impression" (German: Räumlichkeit) and reverberance. Recent attempts have tried to establish a comprehensive criterion which could account for both these factors. However,it is considered justified and worth while to keep the well established criterion, EDT,as measure for reverberance and to introduce a special criterion for lateral reflections (which enhance the spatial impression): Lateral Efficiency(LE) is defined as the ratio between early, lateral energy and the early total energy.

To conclude this survey of criteria it should be mentioned that the balance between the orchestra stage and the audience area may be defined as the ratio between the average values of EDT measured in those two areas. This ratio is called inversion index (I.I.). Normally, values of I.I. should be 1.0 or larger which means that the initial sound should grow more rapidly in the stage area than in the audience area.

As objective criteria we shall in the following be referring to: RT, EDT, C and LE. Frequency dependence will only concern RT and EDT.

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(3) Examples of Auditoria

The selection of auditoria is intended to cover small,medium and large halls, ranging in scope from single over dual to multipurpose halls. With one exception they are halls with which the author is or has been associated:

Hall		year of completion	occupancy	purpose
3.1	Aalborghallen	1952/53	3200/1800/1300	multi-
3.2	Metropolitan Opera,N.Y.	1966	3800	single
3.3	Christchurch Town Hall	1972/73	2650	dual
3.4	Sydney Concert Hall	1973	2690	dual
3.5	Oslo Concert Hall	1977	1700	dual
3.6	Stockholm Berwaldhallen	1979	1300	single
	Projects	expected to open:		
3.7	Odense Concert Hall	1982	1200	dual
3.8	Umeå City Theatre	?	800	multi

(3.1) Aalborghallen (1952/53)

The (3) main purposes of this large hall are: assembly (3200), concert (1800) and drama (1300). Given these large differences in occupancy the architects decided to use a rectangular shape and to divide the hall (incidentally with a partition with high sound reduction value so that the two parts of the hall could be used simultaneously).

Special emphasis was put on the second purpose, concert, so acoustical design aimed at giving the concert hall the highest priority. The orchestra was to be located on a platform in front of the main curtain (the concert hall could also function as opera theatre by lowering the platform to create an orchestra pit). Large movable side reflectors surround the orchestra which also had the benefit of a large canope. The rear seats were placed on waggons so that a reasonable pitch of the seating area was achieved. RT vs. frequency characteristic (measured with an audience present) for the concert hall situation indicate the concern for high frequency reverberation.

The original planned PA system with the speaker units located in baffles above the canopé was not very efficient and had to be supplemented with sound columns at stage level and along the side walls. No commercial time delay system was available at the time of the opening but recently a revised speaker system was installed with time delays.

The drama situation has been the least successful in practical use of this hall. No wonder since RTvalues were not much reduced with the reduced volume so that intelligibility was far from perfect.

None of the more modern criteria have been measured in this hall.

(3.2) Metropolitan Opera, New York (1966).

Grand opera is the single purpose of this hall (occasionally used for ballet, though). The balance of singing and orchestra music is a main concern and the concern for intelligibility is also important.

The general shape is the classical opera auditorium shape but with important qualifications. A survey of classical opera shapes will disclose important variations of shape, especially with regard to the shape of the proscenium zone. Certain auditoria have a shallow proscenium frame with no sound reflecting capacity, others have a deep proscenium frame which represents a transition zone between stage and auditorium. The latter concept was applied in the case of the new Metropolitan Opera with a very convincing result. This was already apparent by the model testing (in a 1:10 scale model) and became also evident in the final testing, which showed values of RT and EDT practically coincident in numerical values and also showed an RT(EDT) vs. frequency curve with good preservation of high frequencies. Speech intelligibility is quite good in the Met which became apparent already at a test performance (with audience) where a speaker at the front stage was clearly heard and understood over the whole audience area.

(3.3) Christchurch Town Hall (1972/73)

The acoustician (A.H. Marshall in association with Engineering Design Consultants, London) has reported to J.A.S.A. (published just a year ago). In cooperation with the architect his design intention was to create a hall with definite emphasis on lateral reflections. This was in accordance with his own experience as well as M.E.Barrons and others.The shape in plan (elliptical) was not particularly suited for this exercise but by applying freely mounted oblique reflectors at the sidewalls in combination with reflecting gallery fronts and gallery soffits it was expected (and later proved) that plenty of

early lateral reflections were produced.
No figures of lateral efficiency seem to have been published but values of RT and EDT show that the hall has plenty of reverberance (increasing from medium to high frequencies). Values of clarity are close to expected values (C_{expect} = -2.9 dB for the empty hall).
A few years ago (1977) speech intelligibility tests were carried out and the results seem remarkably good. In(4) areas of observation the percentage articulation loss of consonants ranged from 9 to 14% against predicted loss (by the actual RT value, 2.7 sec.) from 17 to 37%. (table 1).
No doubt, the results obtained in this hall may be interpreted as significant especially in connection with the problems of future multipurpose halls.

(3.4) Sydney, Concert Hall (1973)

It is impossible here to give a detailed report of the history of the Sydney Opera House (which has been given elsewhere). The final design of the concert hall was the outcome of a thorough model research(1:10 scale models) which clearly had shown the superiority of high vertical side walls, (well framed-in orchestra stage and terraced seating) over a side wall design with stepped wall surfaces and convex ceiling shapes. EDT was used as a test criterion with apparently reliable results.
A special feature of the wooden panelling was the large areas with slotted panels which were meant as a possibility for a final tuning of RT vs frequency curve. By covering some (or all) of the slots it was possible to change the absorption coefficient (vs. frequency).
The test concerts and the objective testing carried out gave the opportunity to correct the frequency dependence and to smooth out a local peak in the low frequency range.
The experiences with this concert hall have been very positive, indeed. Recently the grand organ has been completed and organ performances have also been much appraised.

(3.5) Oslo Concert Hall (1977)

Also this hall had a long design development history partly associated with the questionable shape in plan (a triangle) partly also caused by the considerable time span between preliminary planning and final construction. This

meant ample time to spent on model research which was concerned with many basic problems: location of the orchestra, shaping of the ceiling, balcony or terrace, shaping of the terrace, probable usefulness of orchestra reflectors etc. Main criterion was also in this case EDT. The variation of this parameter throughout the auditorium (model) was also studied.All these investigations and also close cooperation with the architect at all stages resulted in many changes from the simple triangular shape to the final design which became rather complicated, but which, no doubt, enhanced the lateral reflections much more than the original shape.
Oslo Concert Hall was well received by musicians and audience as well. A final tuning of slotted panelling at the side walls increased RT and EDT somewhat over a considerable part of the medium frequency region.
A problem which management had to face after the inauguration appeared by the use of the hall for entertainment concert with heavy amplification. This purpose was of low rank on the priority list (no.1 being concert hall, no.2 congress hall) and the PA system was not designed with this in mind.
A solution was eventually found by an arrangement of curtains (soffits and sides) which is only used for entertainment concerts and pop groups. In this connections objective tests were performed to study the influence on EDT, C and LE.

(3.6) Stockholm, Berwaldhallen

This hall which opened a few months ago may be considered a true single purpose hall, being the home for the Swedish Broadcasting Symphony Orchestra. In a way, of course, it has two purposes:Concert Studio and Concert Hall but they do not pose conflicting demands to the acoustical design.
Originally, the shape was to be rectangular but later it became hexagonal (moderate)which, at least at the main floor results in an increase in lateral reflections. The model (1:10) was mostly tested for values of EDT and I.I. whereas the hall itself also was tested for clarity and lateral efficiency.

Like in Oslo a final tuning was undertaken with the object of increasing values of RT and EDT. The final result is a hall which is a little less reverberant than the one in Oslo but which has remarkable (and much favored) clarity. The arrangement of the audience on three levels (and all around the stage) also tend to reduce reverberance somewhat. The hall has been well received, more experience should be gained before final judgements could be established.

(3.7) Odense Concert Hall

This hall is expected to be finished two years from now. The acoustical design has been very carefully studied in a scaled model and the criteria tested are: EDT, C and LE. The variables in the design have been the diffusing shapes in the ceiling and on the side walls and also the framing in of the orchestra stage. The structural beams provide diffusion in the longitudinal direction and suspended elements under the beams have been installed to diffuse the sound in lateral directions. One of the results from these investigations was that very pronounced minima of LE could be found in positions along one side wall and that they could be partly eliminated by applying triangular prismatic diffusors under the structural beams.

(3.8) Umeå City Theater

This is a project for a multipurpose hall and may not be built in the near future. It is a very flexible scheme which envisage many different configurations for theatre applications. The priority list include several items, the three first are: (1) Opera, (2) Drama and (3) Concert. The occupancy is increased by concert since the stage area may be integrated with the auditorium by letting the proscenium frame disappear and by partly covering the opening to the stage loft with sound reflectors.

(4) Trends in the Acoustical Design of Auditoria

It is rather obvious that acoustical design principles of auditoria be considered in close connection with the purpose of the hall; the number of purposes and also their priority must influence these principles. To design a single purpose hall f.i. a concert hall has always been the highest aspiration of the acoustical designer but admittedly this situation may not occur too often in the future.

The trend invariably seems to go in the direction of dual purpose and multipurpose halls. The general trend in society towards decentralization may besides point in the direction of smaller sizes of halls, more halls between 600 and 2000 seats, fewer halls in excess of 2000.

However, let us first consider the problem of the large hall with dual purpose

f.i. (1) Concert Hall, (2) Congress Hall. We then have to provide good acoustics for both music and speech.
As we have seen through the examples discussed,the straight forward solution, so far, has been to install a good PA system for speech and to design the hall strictly to comply with all the demands of a concert hall. But we have also seen examples of how the promotion of lateral reflections tend to make large halls more suitable to function both for speech and for musical purposes, and it seems very likely that we are only at the beginning of this development and that the future of acoustical design will show more examples of how to increase the influence of early, lateral reflections.
Electro-acoustical systems will be needed for many purposes,like entertainment and pop concerts, but in some instances you may even think of such systems as an aid to create early, lateral reflections (by suitable located speaker units), and this may especially happen in very large and very wide halls where the natural contribution of lateral sound from the side walls is modest. However, even in halls of extreme dimensions we should still consider the possibilities of creating lateral reflections from other surfaces, especially from the ceilings, and this may be done in several ways.
In small and medium sized halls it becomes much easier to provide lateral reflections and in some cases you may leave loudspeakersystems out of consideration, especially if you are free to choose appropriate shapes and dimensions. The classical, rectangular shape and the classical proportions are still much to be recommended in cases where other considerations do not interfere with the design.

To give an idea of the variation of lateral efficiency (LE) in different halls (and also within individual halls) the results of measurements have been gathered in a table (2). The measurements have been made in halls as well as in physical models (in 1:10).
In conclusion: the years ahead may prove to be an interesting period in sound design of auditoria. As the basis we have a fair knowledge of the most important criteria for speech and music, we have quite good tools to guide us in the design process (both physical and computer models) and it is very likely that we shall witness a wide selection of projects, maybe especially if we think in

terms of dual and multipurpose halls.

table (1)

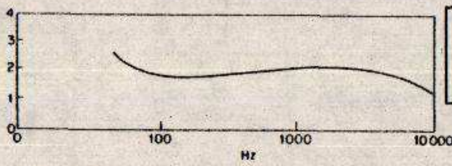
Christchurch Town Hall, % Articulation Loss of Consonants

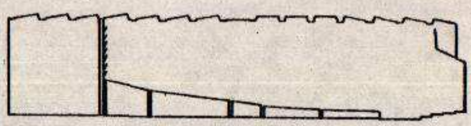
group	distance (m)	ALC, observed	ALC,predicted
S1	15	9	17 - 28
S2	27	14	26 - 37
G1	27	11	26 - 37
G2	28	14	26 - 37

table (2)

Lateral Efficiency, (LE), in various Halls and Models

Hall	occupancy	shape	$LE_{aver.}$	$LE_{aver.}$ (in % of expect.value)	LE_{min}	LE_{max}
Oslo Concert Hall	1600	fan, modified	0.355	89.5	56.5	143
Stockholm Berwald-hallen	1300	hexagon	0.331	84.0	33.2	149
"A"	1500	wide fan	0.120	30.2	16.4	37.8
"B"	2200	slight fan	0.097	25.1	8.0	46.6
Project						
Odense Concert Hall	1200	rectangular	0.332	89.5	67.5	110
Dublin Concert Hall	1300	do	0.504	127	93.5	280
Nordens Hus, Faroe Islands	400	do	o.564	150	93.4	231



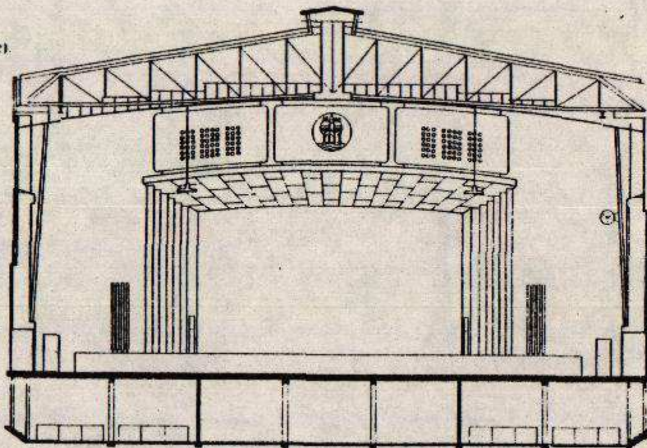


Aalborghallen longitudinal section.

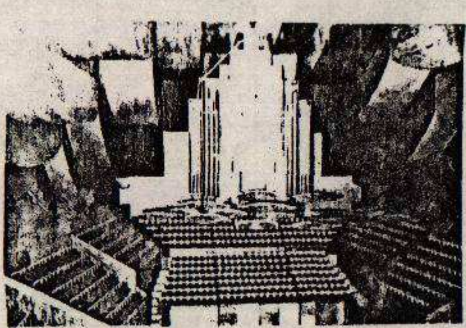
Aalborghallen -- RT v. frequency

(Concert Hall with capacity audience).

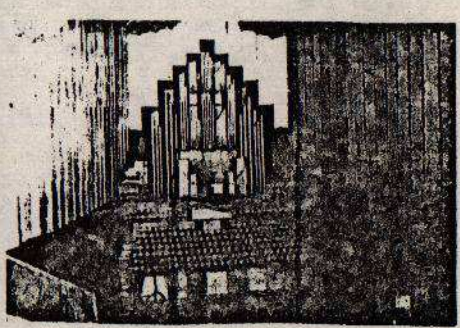
Schematic plans and long section of the Metropolitan Opera House, Lincoln Center.



Aalborghallen- cross section.



Sydney Concert Hall, model of 1st design
view towards organ



model of final design
view towards organ

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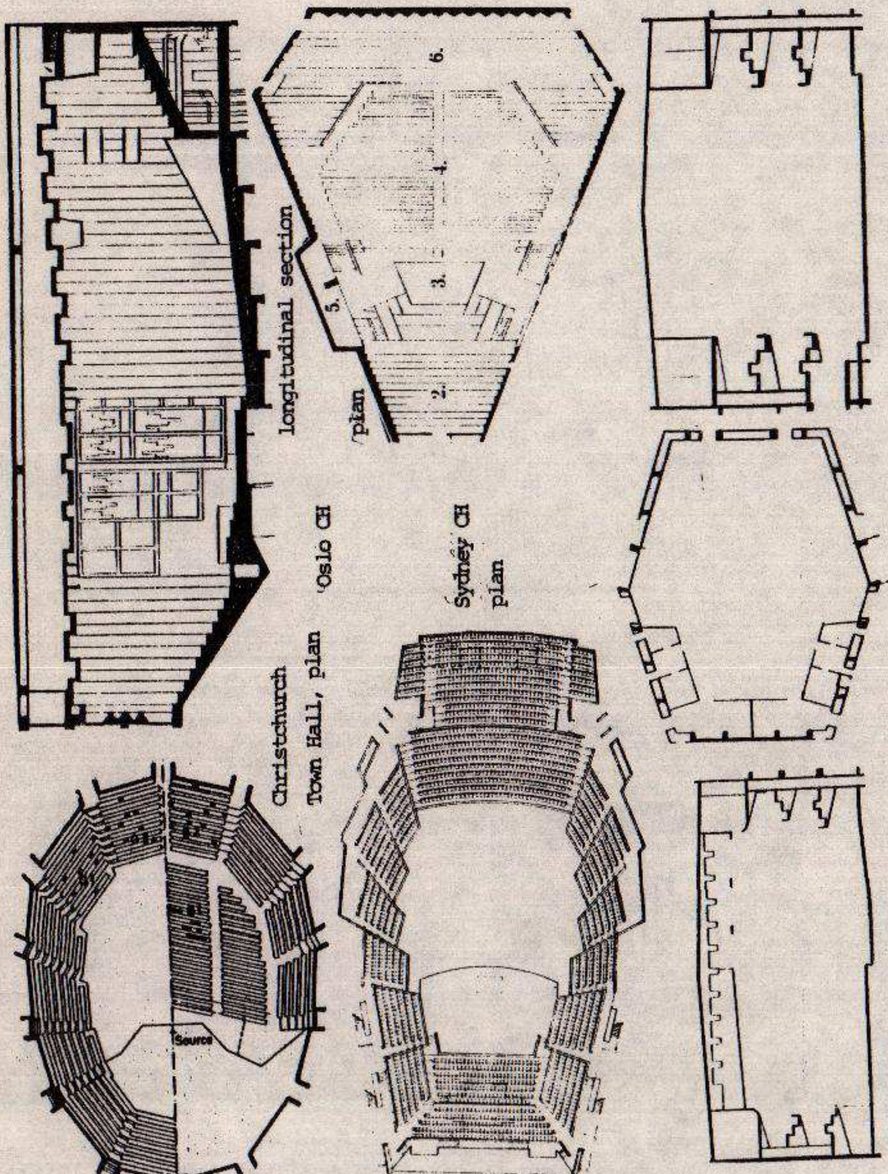

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