OLD AND NEW IDEAS IN CONCERT HALL ACOUSTICS

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INTRODUCTION

Concert hall acoustics is a field in which only few lasting advances have been made during the past century although many acousticians have been attracted by this matter, and although considerable research activities have been devoted to it.

At least two reasons seem to be responsible for this strange situation. One of them is the fact, that many people with quite different background are expert in this field: musicians, music critics, experienced concert-goers, architects, broadcasting and television engineers and - last but not least - professional acousticians. Among the latter category, there are engineers, physicists and several other experts. Another possible reason is that although sound propagation is certainly governed by physical laws, the acoustical reputation of a concert hall cannot be ultimately established or assessed by any objective measurements or calculations even if these account for certain properties of the human hearing, but by the public opinion which is composed in a complex way of musical tradition, of individual listeners' personal habitudes and tastes, by the quality of the performed music and of many other factors which have nothing to do with acoustics.

This is not the place to present a complete historical survey on concert hall acoustics, but it should be recalled that modern room acoustics start with the introduction and investigation of reverberation by W. C. Sabine, and until now the reverberation time seems to be the only objective quantity which has become generally accepted as a measure for the acoustical properties of a hall. But almost as old as the reverberation time is the insight that a proper value of this quantity alone does not guarantee that a particular auditorium will be acoustically successful as a concert hall. Correct reverberation time - whatever this means - is a necessary, but not a sufficient condition for good acoustics.

VERY OLD IDEAS

Among the earlier attempts to find an additional criterion for good acoustics, which could fill this gap one should mention the work of E. C. Wente /1/ who measured the steady state transmission function between two distant point in a room hoping to derive from such "transmission curves" significant information on the acoustics of the room. About at the same time and parallel to these and similar investigations, many acousticians became interested in the eigenfrequencies and eigenfunctions of rooms. The basic idea behind all this research work was that the transmission or frequency curve of a room should be as smooth as possible - a requirement which is self-evident for all those who want to assess the quality of components like microphones, loudspeakers, amplifiers, tape recorders etc. In order to achieve this, some authors recommended that a hall should have particular ratios of dimensions which would lead to a uniform distribution of eigenfrequencies. Other researches proposed that architects should avoid regular room shapes since these would cause mode degeneracy and hence again non-uniform transmission curves. Nowadays we know, that these ideas were correct, but that their application to real rooms are not meaningful because the average frequency spacing of their resonances are - except for very small enclosures or at very low frequencies - extremely small compared to their halfwidth. Therefore the peaks and valleys of a transmission curve are brought about by the superposition of numerous vibrational modes with virtually random amplitudes and phases, and shifting a couple of eigenfrequencies means just re-shuffling the cards.

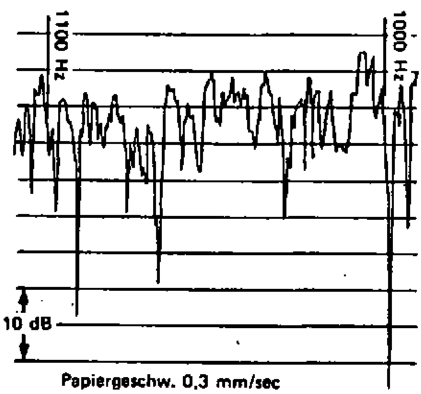

Fig.1: Part of a transmission curve (after /2/)

Even the transmission function between a sound source and a receiver turned out to be of little use for judging the acoustical quality of an auditorium as can be seen from the fact, that the detailed structure of such a curve (see Fig.1) is completely different when the receiver position is changed by say one meter although the listening conditions usually are not. In 1954, M. Schröder developed a theory of the statistical parameters of such curves /3/, and it was proved that the average spacing of their maxima, or the mean level difference between maxima and minima are the same for virtually all halls or are just a simple function of the reverberation time. Nevertheless, the theory of linear systems tells us that the transmission function of any system contains the complete information on the systems' properties. Obviously, the information relevant for concert hall acoustics is not just at the surface of this function but is hidden in its interior structure. Up to now, nobody has found out which kind of processing processing should be employed to reveal this information - apart from Fourier transformation which yields the impulse response of the room.

OLD IDEAS

After the second world war there was a great need for the construction of new concert halls. Furthermore, the growing interest in music as well as in other cultural events led to increasingly larger auditoria. This tendency augmented the acoustical problems caused by the architects' desires to create modern halls with new shapes and in a style which was to reflect modern life more readily than those old-fashioned halls which had been in use until then.

This situation led some researchers to the conclusion, that the whole matter had to be reconsidered from a purely physical point of view. Special emphasis was given to the geometrical standpoint which considered the sound field in a closed room as being composed of the direct sound and a great number of reflections rather than of steady state or decaying vibrational modes. Accordingly, much research work was concentrated on the temporal and directional distribution of the sound reflections which were thought of as sound pulses propagating along straight rays. Furthermore, the mutual masking of such sound components and its dependence on time delays, amplitudes and directions was studied very thoroughly. Many authors invented new sound field criteria based upon the temporal distribution of reflections. Some of them are still useful nowadays, others have fallen into oblivion.

But one of these ideas should be described in some more detail, namely that of diffusion. These term describes the fact, that the sound in an auditorium arrives at the listener not only from ahead as in free space but from many different directions. Complete diffusion means that there is no prevailing direction of sound incidence but that the whole energy is uniformly distributed over all directions. To characterize the uniformity of the directional distribution a special quantity was introduced, called directional diffusion /4/:

$$d = 1 - \frac{1}{\langle E \rangle} \iint [E(\varphi,\vartheta) - \langle E \rangle] d\Omega \qquad (1)$$

Here, $E(\varphi,\vartheta)$ denotes the steady state energy arriving from a direction characterized by two angles φ and ϑ, the bracked indicates averaging over all directions. In Fig. 2, the directional distribution of some steady state sound fields is presented.

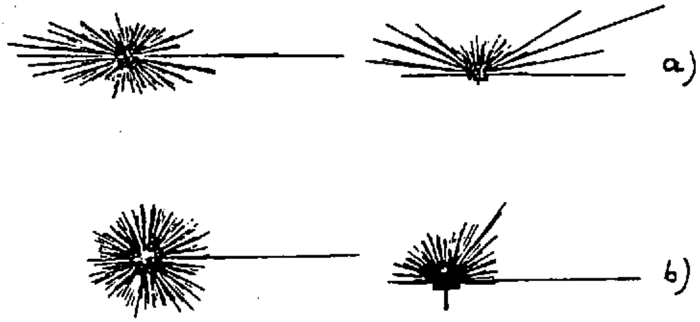

Fig.2: Directional distribution of steady state energy in two opera theatres. a) Düsseldorf, b) Münster; left: top view, right: side view (after /5/).

The uniformity of the directional distribution of reflected sound energy depends on the absorption of the enclosure and on its shape. Rooms of simple geometry will favour the dominance of certain directions of incidence whereas complicated shapes and in particular wall irregularities tend to smooth the distribution and hence to increase diffusion. In the traditional concert halls which were constructed in the 19th or at the beginning of the 20th century there are many of such irregularities, partly for constructional and partly for decorative reasons: there are coffered ceilings, balconies supported by pillars, niches, statuettes and many other plastic decorations. Since many of these old halls are famous for acoustical reasons or even have set the standard for excellent concert hall acoustics it was concluded that it is their irregular shape and hence the diffusion caused by it which makes them superior to many modern halls, and furthermore, that a diffuse sound field would create the listener's subjective impression of being embedded in sound. This "spatial impression" as it was called later was believed (and still is!) to be an indispensable ingredient of a good acoustical atmosphere. Since it is different from reverberation, diffusion seemed to be what has been looked for since long, namely the missing link between what listeners hear and want to hear in a concert hall on the one hand, and physical sound field properties and even constructive data on the other.

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During the following years, several courageous acoustical consultants tried to draw practical conclusions from these ideas and recommended architects to translate the "wall irregularities" from the 19th century style into modern language. One of the results is the Beethovenhalle in Bonn which was opened in 1958. This hall, which is not a pure concert hall but rather a multipurpose auditorium got a highly structured ceiling and side walls covered with large cylindrical segments. This treatment was chosen not only to avoid the unfavourable effect of the curvature of these areas but also to enhance sound field diffusion. The result was disappointing for the protagonists of diffusion: its acoustics is not bad, for certain types of music it is even excellent, but it failed to show what it was expected to, namely a particularly marked "spaciousness" of the acoustical impression.

NEW IDEAS

The subsequent period was characterized by great efforts to study the interrelations between the physical structure of sound fields and the subjective effects they have on listeners. The test fields are usually synthesized with more or less complex loudspeaker arrangements in an anechoic room which allow to simulate many reflections with adjustable strength, time delay and direction. Several research groups have performed experiments of this kind and have obtained many interesting results, which cannot be discussed here in detail.

One particularly important investigation was carried out by Barron /6/. His work was based upon Marshall's idea /7/, that subjective spaciousness is effected by sound reflections from lateral directions, and on the previous experimental investigations of Reichardt and Schmidt /8/ on the spatial impression in synthetic sound fields. Barron's first experimental set-up consisted of two loudspeakers, one simulating the direct sound, and the other one used for the simulation of one single reflection with variable strength, time delay and lateral direction. From many experiments with this and other arrangements of increasing complexity he concluded that a quantity, now called "early lateral energy fraction" and defined by

$$S = \frac{\int_0^{80ms} E(\Theta,t)\cos\Theta\, dt}{\int_0^{80ms} E(\Theta,t)(1-\cos\Theta)\,dt} \qquad (2)$$

is closely related to the spatial impression. In this equation, Θ is the angle between an imaginary axis connecting both ears of a listener and the direction of incidence. It tells us, that only those reflections which are delayed with respect to the direct sound by no more than 80 ms contribute to the spatial impression and this the more, the larger is the deviation of their direction from that of the direct sound.

Quite a different investigation, carried out by M. R. Schroeder and his co-workers /9/ pointed into the same direction. They compared 25 European concert halls by recording music in them and by presenting these records to test persons in an anechoic room employing a sophisticated reproduction system. The answers of the test persons were processed by multidimensional scaling and led to the result, that listeners prefer sound fields which produce only partially coherent sound signals at both their ears. In a large hall, differences between both ear signals are brought about only by reflections arriving from lateral directions but not from directions in the median plane of the head. This finding underlines again the important role of lateral sound reflections in a concert hall.

The quantity defined in eq.(2) has the great advantage that it can be measured with relatively simple equipment in existing concert halls as well as in models of non-existing ones, and that it can be calculated with a personal computer from drawings. Thus, the early lateral energy fraction could be employed as a tool for the acoustical design of concert and other halls, provided there is enough reliable information on its optimum range. It can be used as well to compare basic room shapes at least qualitatively in order to find out, which of them would be suitable for a concert hall and which have to be ruled out from the outset.

One recent attempt of this kind has been devoted to polyhedral enclosures with horizontal floor and ceiling /10/. The floor can be left out of consideration because the audience on it is a nearly perfect sound absorber. Furthermore, a preliminary study has shown that the contributions of the ceiling to the nominator and the denominator of eq.(2) nearly cancel each other and hence can be neglected as well. For the calculation of the early lateral energy fraction, cos 0 has been replaced by cos 0 to make the results comparable with values obtained by measurements for which this modification is useful. The energies E of the reflections have been calculated using the method of mirror images, assuming an absorption coefficient of 0.1 for all walls.

Fig.3 compares several rectangular hall shapes, the assumed ground area was 1000 m for all of them. The obtained results are marked by differently shaded areas. The densities correspond to the S-intervals 0 to 6%, 6 to 12%, 12 to 25%, 25 to 50% and 50%. - Next to the sound source which is indicated by a cross the amount of lateral energy is always very small, of course. Its highest values are found next the side walls, and the most favourable shape seems to be that of a narrow rectangle with the sound source at one end of it. - In Fig.4, results for some trapezoidal shapes with an area of 600 m are presented. They indicate, that the fan shape is inferior to the rectangle as long as the sound source is in the narrow part. The reverse statement holds for the "inverse fan shape", which is of no practical use in its pure form. However, designers could be take advantage of its favourable effect by subdividing larger halls or by shaping balcony faces etc. in this way.

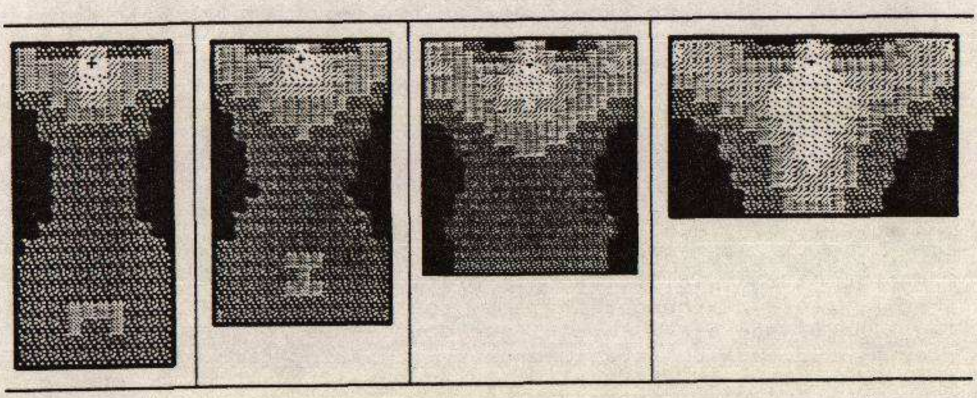

Fig.3: Early lateral energy fraction in rectangular halls (after /10/)

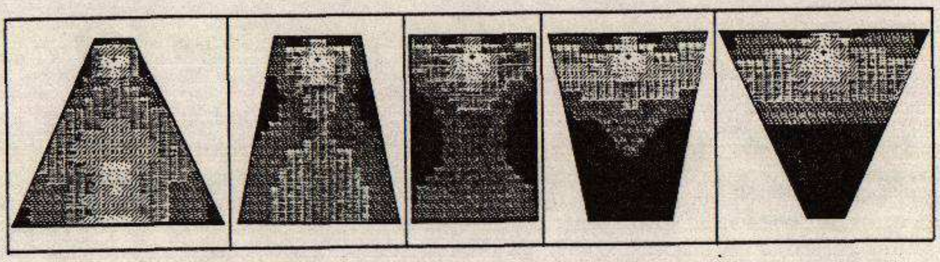

Fig 4: Early lateral energy fraction in fan-shaped halls (after /10/)

Further investigations have led to the result, that scattering of sound as caused by acoustically rough side walls or ceiling does not significantly contribute to the early lateral sound fraction unless the scattering characteristics shows a particular anisotropy.

CONCLUSIONS

From the above-mentioned and similar investigations the general conclusion can be drawn that the conventional shape of concert halls, namely the rectangle with narrow walls - both with and without decorations - is unsurpassed in acoustical respect. This is bad news for ambitious architects since it means going back to the archtitecture of the past century. It is also bad news for many acousticians because it means that much reseach work on concert hall acoustics has been done in vain.

On the other hand, we should not be too surprised at this conclusion. It is a consequence that our musical life is mainly traditional not to say historical. The program of most public concerts is restricted to such works which have been composed within a period of about 300 years beginning with Vivaldi, Bach and Handel and ending with composers of the late 19th and the early 20th century. A similar statement holds for the instruments used to perform these works. Their construction is sanctified by the tradition. The shape of the string instruments and the material they are made of have remained unchanged since several centuries, and the results of all attempts to make differently shaped violins are curiosities at best. The wind instruments are of younger age, but their technical development has also ceased since long. If we consider a concert hall as some kind of musical instrument it is just consequent to prefer that kind of halls which have formed our expectation of what a fine concert should sound like.

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