Acoustical Design of the Grieg Memorial Hall in Bergen

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(Received: 1 March, 1984)

SUMMARY

The Grieg Memorial Hall in Bergen, Norway, finished in 1978, is a multi-purpose hall primarily intended for concerts. To cater for other uses, it is equipped with a large stage and constructed in such a way that it can be converted to serve for theatre, opera, ballet, shows and congresses. The orchestra enclosure is demountable and a loudspeaker system for speech reinforcement can be lowered from the ceiling just in front of the stage opening. The shape of the hall was designed using a computer program mathematical model for three-dimensional sound ray tracing. The hall being fan shaped, sufficient lateral reflections are provided by large reflecting elements hung freely below the ceiling. The resulting distribution of reflected sound energy gives the hall a fine balance between reverberance, fullness of tone and clarity. Measurements of pulse response, reverberation time and speech intelligibility tests are presented.

INTRODUCTION

The Laboratory of Acoustics/ELAB was responsible for the final design of the Grieg Memorial Hall, in cooperation with the acoustical consultant and coordinator for the hall, Helmer Dahl. Our starting point was difficult as the concrete construction for the walls, the roof and the audience area had been finished (despite protests from Helmer Dahl) when we were asked to find a favourable room shape design. The main
Fig. 1. The Grieg Memorial Hall. Audience, 1500; volume, 18,000-20,000 m³ as a concert hall and more than 30,000 m³ as a theatre. 1, concrete constructions; 2, stage house for theatre; 3, orchestra enclosure; 4, side wall reflectors; 5, freely hanging reflectors below the ceiling; 6, control rooms for theatre lighting, radio and TV; 7, opening for theatre lighting; 8, ventilation room; 9, movable loudspeaker units (five).

Fig. 2. The Grieg Memorial Hall.

Fig. 3. The orchestra enclosure.
problem was the fan shape; this gave unsatisfactory distribution of sound and particularly the lateral reflections in the audience area were too weak. The design therefore had to be unconventional (Figs 1–3), giving the hall a distinctive character. The design period was long and the calculations of sound distribution were extensive, but the response, both from local performers and visiting conductors and orchestras, has been very favourable.

**COMPUTER MODELLING OF THE ROOM SHAPE**

Our investigation used three-dimensional sound ray tracing in mathematical models of the room. The computed data enabled us to study simultaneously the space, time and directional distribution of reflected sound energy in the audience area. Earlier investigations of existing concert halls and simple room shapes had given valuable experience for the evaluation of the computed data. Our main design guidelines for this hall were as follows:

—good acoustics for any performance must imply satisfactory sound quality for all seats; i.e., even distribution of reflected sound energy in the audience area.

—a satisfactory balance between early reflections (time delay 10–30 msec) and late reflections (time delay 50–100 msec). (The late reflections are very important, giving music a special non-distinct character called fullness of tone.)

—strong early reflections giving a distinct sound (necessary for theatre acoustics).

—the directional distribution of reflections in the audience area must include many lateral incidences (time delay 10–100 msec). (Lateral incidences are responsible for spatial impression and contribute significantly to acoustical quality.)

—the orchestra enclosure must be properly designed in terms of shape, dimensions and materials. A good balance between the various sections of the orchestra and between the orchestra and vocal or instrumental soloists must be provided. A good blend of sound from the various instruments is also important. The musicians must be able to hear themselves and their nearby performers in the orchestra.

The relevant references for these guidelines are given in Ref. 4.

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Fig. 4. Investigation of the sound energy distribution on the audience area using sound rays in a three-dimensional mathematical model of the hall. The point source is positioned in the middle of the orchestra enclosure. The ray impingements on the audience area are drawn as dots on a plan view of the area. Due to symmetry the calculations are performed in one half of the room. Time delay is calculated for each impingement and they are sorted in time delay intervals. The intensity of dots in each interval is a measure of the sound intensity. A, Room shape that gave uneven sound energy distribution; B, final room shape that gave a satisfactory even distribution.

Fig. 5. First order reflections from freely hanging reflecting elements below the ceiling. Time delay will be 60–100 msec. The computed ray impacts on the audience area are shown to the right. The incidence direction is indicated as a short line drawn from the impact point.
Fig. 6. First order reflections from the side wall reflecting elements. Time delay (msec) is indicated.

Fig. 7. First order reflections from the ceiling, the orchestra enclosure and the freely hanging reflecting elements below the ceiling. The time delay (msec) is indicated.

Fig. 8. Calculated echograms for two positions in the audience area. The ray impliements are registered on spheres (radius 1 m) hanging freely, close to the audience area. The echograms to the left are drawn with 10 msec resolution, and the echograms to the right show every single reflection on the time axis. We then calculated the room acoustical parameters, definition, $D$, defined by Thiele,\(^a\) and centre of gravity time, $t_c$ (first order momentum of the echogram), defined by Kürer.\(^b\)

$$D = \frac{\int_0^{t_0} t\cdot P(t)\,dt}{\int_0^{t_0} P(t)\,dt} \quad t_c = \frac{\int_0^{t_0} t^2\cdot P(t)\,dt}{\int_0^{t_0} P(t)\,dt}$$

$P(t)$ is the power function for all ray impacts on the sphere. For practical reasons the integration time is restricted to $\frac{1}{2}$ sec. For both echograms we get $D = 0.42$ and $t_c = 0.68$ msec. The measuring positions A and B are shown in the figure.
Fourteen alternative computer models were investigated (Fig. 4). The main problem was the fan shape which made it impossible to obtain sufficient side wall reflections in the middle part of the hall using conventional designs. The solution to this problem was to produce the effect of a smaller hall by using freely hanging reflecting elements below the ceiling (Fig. 5). The size of the plane reflecting front surface is 10–20 m², and the angle of the surfaces was carefully calculated. For aesthetic reasons these elements are not plates but were shaped by the architect Knud Munk as square cones or pyramids, partly with steps, as seen in Fig. 2, therefore they also have a desirable diffusing effect. The side walls were designed to give strong lateral reflections on the audience area (Fig. 6). The lower part of the walls have large reflecting elements,
tilted about 5 degrees. The stepped ceiling gives an even distribution of early reflections in the audience area (Fig. 7). The movable ceiling in the orchestra enclosure was made as a continuation of the ceiling in the hall.

The final hall design gave a satisfactory even distribution of reflected sound energy in the audience area, as Fig. 4 indicates. In Fig. 8 the calculated echograms show many late reflections (time delay 50–100 msec), giving a fine balance between early and late energy that is desirable for music performances. Further analysis of the echograms has shown that these late reflections are mainly coming directly from the side walls or the freely hanging reflectors. They therefore have the desirable lateral incidence on the audience area.

The measured impulse responses were in excellent agreement with our computed data (Figs 9–11). This was also verified using a highly
directional microphone to investigate the finer details in the echograms (Fig. 12).

MATERIALS AND CONSTRUCTIONS

An important design criterion for a concert hall is a sufficiently low background noise level in the hall (not more than N-20 or 25 dBA). As the traffic noise level outside the building was high, a heavy concrete construction was used. There is also a large foyer all round the hall, serving as a buffer zone. In the gaps between the zig-zag shaped concrete walls there are gypsum partitions, having a reflecting sandwich plate 6–7 cm thick (gypsum + plywood) that faces the hall. The large ceiling of the hall and orchestra enclosure have been made sound reflecting by the use of 1/2 mm steel plates coated with a 3 mm vibration damping layer. The same construction has been used for the reflecting elements below the ceiling and for the elements of the side walls. The orchestra enclosure can be moved to the rear part of the stage house. We therefore had to use a lightweight wall construction; 4 mm plywood with a vibration damping layer was chosen (Fig. 13). The concrete floor in the hall is covered with a sound reflecting neoprene layer. The only absorbents are the moderately upholstered seats and some areas on the upper parts of the walls having split panels.

These materials gave a measured reverberation time of 2 sec, as shown in Fig. 14, with an audience of 1500.

ELECTROACoustics

The loudspeaker system for speech reinforcement (designed by SEAS) has five separate units that can be lowered through the ceiling just in front of the upper part of the stage opening (Fig. 1). The central unit is directive and gives a satisfactory even sound distribution over all of the audience.
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Fig. 15. Speech intelligibility test using nonsense test words. The percentage of correct sounds (3 sounds in each word) is given for nine different test positions in the audience area. 20 untrained test subjects were used and 125 words were read.

(area, but only a little sound radiation to the ceiling and walls. The four side units are used for panoramic effects. As the hall is intended primarily for concerts and symphonic music, high speech intelligibility requires a controlled distribution of sound. The audience will perceive this as a reduction of the long reverberation time. The directivity of the loudspeaker system is nearly independent of frequency. This has been obtained by controlling the number of loudspeaker elements in operation

(which reduces the effective length of the unit against higher frequencies) and by using a multi-way system. The central unit is made of 29 loudspeaker elements; the dimensions are 3 m x 1 m x 1/2 m. The four side units have 9 elements each; the dimensions are 3 m x 1/2 m x 1/2 m. More recently supplementary units for pop music have been installed.

SPEECH INTELLIGIBILITY TEST

A speech intelligibility test was performed using nonsense double test words. Random sequences of consonants (c) and vowels (v) are generated by a computer in the order:

cvcvcvc cv[cvc]v

For instance:

MEIVIKJASJ FU[BYP]AUT

Such nonsense words can easily be pronounced in Norwegian. In the empty hall these words were read with a signal-to-noise ratio of 25–30 dB. An untrained group of 20 persons (age 20–50 years) listened to this test and answered the request for 3 sounds in the second word, indicated in the square bracket above. The full test had 125 double test words. The mean value of the percentage of correct sounds for the test group is given in Fig. 15. The results indicate high speech intelligibility. This test used a special laboratory loudspeaker unit in the middle of the orchestra enclosure when saying the test words. In another test using the centrally positioned loudspeaker below the ceiling, the results were even better.

CONCLUSIONS

The hall was finished in May 1978 only a few days before the Bergen International Music Festival. There was no time left for adjustments, and no material changes have been made since. Experience from the festivals has been very positive, and there has been no need for modifications. Musicians, conductors and audience members have reported their impressions as: 'Satisfactory fullness of tone and spatial impression, but at the same time a distinct sound'.

Actually, in spite of the 2 sec reverberation time and the large
dimensions, the hall is also good for smaller ensembles and soloists. The resulting evenness of sound distribution in the audience area was surprising. We believe that this must be due to the many diffusing elements with a great variety of dimensions: from 0.1–0.3 m for light and ventilation units in the ceiling and up to 6–8 m for the freely hanging reflecting elements below the ceiling.

The most important experience from this project was that we succeeded in designing satisfactory concert hall acoustics, despite the difficult starting point given to us in the already finished concrete structure. Only due to our computer technique for sound ray tracing could we predict in advance a satisfactory sound distribution, and thereby convince the building committee and the architect of the necessary unconventional redesign of the hall. The verification of these calculations by the control measurements in the hall clearly shows the great value of using computers for designing room acoustics.

REFERENCES

2. S. Strøm, Distribution of reflected sound rays in models of existing concert halls (in Norwegian), Technical report LBA 381, June 1971.