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Design and Measurement of Short Reverberation Times at Low Frequencies in Talks Studios*

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Various types of acoustic treatment have been used in the new talks studios of the Danish Broadcasting Corporation. For verification, reverberation times of about 0.1–0.2 s were measured in one-third-octave bands from 80 Hz to 8 kHz using a new time-reversed analysis technique. It is demonstrated that the ringing of the filters would have introduced errors at low frequencies if traditional forward analysis had been used.

0 INTRODUCTION

Talks studios are generally designed with a rather short reverberation time. The new studios of the Danish Broadcasting Corporation are designed with reverberation times of about 0.1–0.2 s. However, very short reverberation times cannot be measured in one-third-octave bands using traditional measuring techniques because of the ringing of the filters. A new measuring technique, which is based on a time-reversed analysis, has been used for these measurements, and the results were compared with traditional methods using forward analysis. The interrupted noise method and the integrated impulse response method have both been used, and the relation between limits for reliable results and the choice of measurement setup parameters has been closely considered.

1 ACOUSTIC DESIGN OF TALKS STUDIOS

1.1 Review of Acoustic Design Criteria

In the past the BBC has made comprehensive investigations with the purpose of finding the optimum value of the reverberation time and the shape of the reverberation time–frequency characteristic that should be preferred. BBC experience reported in 1959 by Gilford [1] has shown a reverberation time of about 0.3 s to be the optimum. Further experience and controlled experiments show that the reverberation time should be independent of frequency from 63 Hz to 8 kHz. In 1970 another BBC investigation [2] concludes that a degree of bass rise is acceptable, depending on the speaker, the microphone, and the microphone distance. A permissible maximum reverberation time of 0.73 s at 63 Hz is suggested.

According to BBC investigations, published in 1980 [3], the preferred value of the reverberation time is dependent on the volume. The preferred value of the

reverberation time increases somewhat with volume.

Talks studios are still designed successfully according to the BBC reverberation time criterion [3]. This criterion curve shows mean values in the frequency range of 500 Hz to 2 kHz as a function of room volume. However, the reverberation time of recently designed talks studios in some European broadcasting corporations tends to be lower than that suggested by the BBC. The lowest values are between 0.1 and 0.2 s, taken as mean values in the frequency range of 500 Hz to 2 kHz.

For about the last 10 years the Danish Broadcasting Corporation (DR) has designed talks studios according to [4] with the following criterion: reverberation time $\leq 0.2$ s with a permissible bass rise to about 0.4 s in the frequency range of 63 Hz to 100 Hz. DR studio 21 was designed in accordance with this criterion.

In some cases there have been complaints about sound coloration at low frequencies ("boominess"). Therefore an attempt was made to design a talks studio with a short reverberation time, $\leq 0.2$ s, and, if possible, without any bass rise. DR studio 8 was designed with a relatively simple acoustic treatment. The reverberation time is below 0.2 s in the frequency range of 80–8000 Hz.

The acoustic designs of these two DR talks studios are described hereafter. Simplified plans and sections of the two studios are shown on Figs. 1 and 2 to illustrate their construction and acoustic treatment as well as their characteristic differences. Both are floated “box within a box” structures.

1.2 Acoustic Design of DR Studio 21

1.2.1 Construction

The studio is a DR standard construction according to [4], where the floated box consists of a self-bearing three-layer gypsum board on a 60-mm concrete floor, floating on neoprene. The opposite surfaces of the limiting structure are parallel. The gypsum board construction may contribute a little to the low bass absorption (see Fig. 1).

1.2.2 Acoustic Treatment

Walls. The acoustic treatment consists mainly of modular absorbers mounted between two cable ducts. The modular absorbers are all of the same construction. The absorbers are based on a steel U profile frame, $H \times W \times D = 1.8 \times 0.6 \times 0.08$ m. The frame is divided into two parts by a 1-mm steel membrane mounted 50 mm behind the front of the frame. The spaces both in front of and behind the membrane are provided with layers of about 50-mm mineral wool. The modular frames are placed so that the back of the frame is 20 mm from the wall. The total depth from the front of the frame to the wall is 100 mm. Thus the absorber is a combination of a porous absorber and a membrane absorber. The modular absorbers are mounted with a distance of 10 mm between neighboring modules. The absorbers are therefore also expected to act as slit absorbers. The acoustic treatment of the upper parts of the walls consists of a porous absorber (25-mm glass wool with a 25-mm space behind).

Ceiling. The acoustic ceiling is 22% perforated standard metal cassette ceiling, suspended about 0.5 m, with a layer of 125-mm mineral wool.

Doors. The doors are premanufactured standard doors. They are both provided with DR standard door absorbers, consisting of 25-mm glass wool, covered by 33% perforated steel surface.

Windows. There are two windows (the control

---

Fig. 1. Plan and sections of DR studio 21. 1—50-mm mineral wool; 2—1-mm steel membrane; 3—25-mm glass wool; 4—perforated standard metal cassette ceiling; 5—125-mm mineral wool; 6—carpet on concrete floor. (a) Longitudinal section. (b) Plan. (c) Cross section.
window and a window to the exterior). The windows will contribute a little to the bass absorption.

Floor. The concrete floor is covered with a carpet.

1.3 Acoustic Design of DR Studio 8
1.3.1 Construction

The studio is a 15-year-old traditional heavy concrete/brick wall construction floated on neoprene. The opposite surfaces of the limiting structure are nonparallel (see Fig. 2).

1.3.2 Acoustic Treatment

General. The acoustic treatment was renewed in 1988. From the old acoustic treatment the lining of the ceiling and the walls consisting of 13-mm gypsum board on 80-mm-thick posts is still retained. The space behind the gypsum board is filled with 75-mm mineral wool. This treatment contributes to the low-frequency absorption.

Walls. The acoustic treatment of the walls consists

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Fig. 2. Plan and sections of DR studio 8. 1—40-mm glass wool covered with fabric mounted in steel frames; 2—mineral wool, various thicknesses; 3—13-mm gypsum board; 4—perforated standard metal cassette ceiling; 5—carpet on concrete floor. (a) Longitudinal section. (b) Plan. (c) Cross section.
of 50-mm modular steel frames with 40-mm glass wool covered with fabric. The standard width of the modules is 0.9 m. The modules reach from the cable duct to the ceiling. Behind the modular frames with glass wool is mineral wool of various thicknesses. Behind the mineral wool is an air space of varying depths.

**Ceiling.** The acoustic ceiling is a 22% perforated standard metal cassette ceiling (with 50-mm mineral wool) mounted at a distance of about 100 mm from the gypsum board surface.

**Doors.** The doors from the old construction remain. During renewal they have been provided with DR standard door absorbers (25-mm glass wool covered by 33% perforated steel surface).

**Window.** There is only one window, the control window. Although the window is not a part of the acoustic treatment, it contributes a little to the low-frequency absorption.

**Floor.** The concrete floor is covered with a carpet.

### 1.4 Comparison of the Designs of the Two Studios

The main differences in the acoustic treatment of the two studios concern the walls and the ceiling.

The walls in studio 21 are dominated by the rather complex modular absorbers which, when mounted, have a total depth of only 100 mm.

In studio 8 the acoustic treatment of the wall is less complex than in studio 21. The walls are all provided with a gypsum board membrane. Generally the porous absorbers are thicker and mounted at a larger distance from the limiting surfaces. Thus the studio 8 solution (concerning the walls) needs more space than that of studio 21.

The total building height is about the same for both studios. Therefore the height of the "inner box" is dependent on whether the ventilation ducts are placed inside or outside the inner box.

The ceiling of studio 21 is suspended about 0.5 m, which assists the low-frequency absorption. This is possible because the ventilation ducts have been placed inside the box. The absorption is, however, reduced by an amount corresponding to the space used for the ventilation ducts.

In studio 8 the ventilation ducts are placed outside the box. Therefore less space has been left inside the box for the acoustical ceiling. The perforated metal ceiling surface is the same in both studios, but in studio 8 the ceiling has been mounted only about 100 mm below the gypsum board membrane.

### 2 MEASUREMENT METHODS

No suitable and convenient measurement method is found in any standard. The international standard ISO 3382 [5] describes field measurements of reverberation time, but guidelines for the measurement of short reverberation times are not included. Further, the standard is completely out of date since the main contents is more than 15 years old and the measurement technique has evolved considerably during this period. Some useful hints are found in ISO 354 [6], but the measurement of short reverberation times in studios is outside the field of application and not possible using the method described. Consequently, the measurement procedure must be defined utilizing experience from other practical measurements and the new possibilities offered by modern instrumentation.

In the traditional method a broad-band noise source is used, and after the source has been switched off, the decay curve can be recorded. However, this curve can have strong fluctuations due to the stochastic character of the excitation noise, and several decay curves should be evaluated in each position. Using today's measuring techniques the decay curves from repeated excitations can be averaged into an ensemble averaged decay curve with much reduced fluctuations. Extending the ensemble averaging to include spatial averaging gives rather smooth decay curves, and it seems reasonable to assume that these curves are a good basis for the evaluation of reverberation time.

Another traditional method is the use of a pistol shot as an excitation signal. By this method the impulse response of the room is measured. As shown by Schroeder [7], the decay curve can be calculated from a backward integration of the squared impulse response. One major quality of this method is that there will be no stochastic fluctuations, so one excitation in each position will be sufficient to get a decay curve equivalent to the ensemble averaged decay from an infinite number of excitations using interrupted noise. Spatial averaging can be made by ensemble averaging over all source and receiver positions as described.

A special method, which has occasionally been used, is a pure-tone excitation of separate low-frequency modes in the room and omitting any filter in the measuring system. In this way the decay of separate modes can also be measured for very short reverberation times. However, the method is very time consuming, and it will not work if the natural frequencies of two or more modes are so close that they cannot be excited separately. For these reasons the method can only be a supplement for very special situations.

### 2.1 Limitations Caused by Bandpass Filters

Reverberation time measurements are usually analyzed in one-third- or one-octave bands. However, such bandpass filters can influence the measurement due to the filter ringing, which can give rise to a characteristic waving of the decay [Fig. 3(a)]. According to Jacobsen [8], reliable decay curves are obtained only if

\[ BT_{60} > 16 \]  

(1)

where \( B \) is the bandwidth of the filter and \( T_{60} \) is the reverberation time to be measured. If requirement (1) is not met, the evaluated reverberation time can be too short or too long, that is, the sign and size of the error are not predictable.

However, in Jacobsen and Rindel [9] it has been
demonstrated that reversing the time signal to the filter leads to much less distortion of the decay curve [Fig. 3(b)]. It has been found that if the upper 5 dB is excluded from the evaluation, requirement (1) can be replaced by

$$BT_{60} > 4.$$  \tag{2}

It should be noted that there is no distinct boundary between acceptable and unacceptable decay curves. An important observation from Fig. 3 is that the distortion of the time-reversed decays does not affect the slope of the main part of the decay curve; only the upper part is slightly distorted.

For measurements in one-third-octave bands the limit for reliable results at 100 Hz is changed from 0.7 s to 0.17 s when time-reversed analysis is used instead of forward analysis.

The beneficial influence of reversing the decay signal is due to the fact that the impulse response of the filter is asymmetrical. Fig. 4 shows the impulse response of a one-third-octave band filter; the "tail" of the function gives rise to a decay, which should be shorter than the decay to be measured.

2.2 Limitations Caused by Detector

When measuring short reverberation times it is important to choose the averaging time of the detector short enough to avoid influence on the decay curve. Using a device with exponential averaging (time constant $\tau_d$) it has been shown in [8] that the averaging time $T_{av}$ should obey the requirement

$$T_{av} = 2\tau_d < \frac{T_{60}}{14}.$$  \tag{3}

Here again $T_{60}$ is the reverberation time to be measured.

If requirement (3) is not met, the evaluated reverberation time will be too long.

However, since the response of the detector is much faster when the signal increases instead of decreases, it will be of great advantage to use time-reversed analysis. According to [9], requirement (3) can then be replaced by

$$T_{av} = 2\tau_d < \frac{8T_{60}}{14}.$$  \tag{4}

The influence of the detector is illustrated in Fig. 5 for forward as well as time-reversed analysis. It can be seen that only the upper part of the decay curve is influenced when time-reversed analysis and long averaging times are used. Further investigations reported in Rasmussen and Petersen [10] have indicated that the reverberation times deviate less than 1% from the correct values if conditions (1)–(4) are fulfilled, and the evaluation range does not include the upper 5 dB of the decay.

2.3 Interrupted Noise Method

In the traditional method a broad-band noise source is used, and after the source has been switched off, the
decay curve is recorded on a level recorder. However, this curve can have strong fluctuations due to the stochastic character of the excitation noise, and several decay curves should be evaluated in each position. Using the measuring technique of today, the decay curve can be held in the memory of the instrument. This has made it possible to average the decay curves from repeated excitations to an ensemble averaged decay curve with much reduced fluctuations. The ensemble averaging can be extended to include a spatial averaging of a number of different source–microphone combinations, which will lead to a rather smooth decay curve, giving a precise description of the reverberation process in a particular room. An example is shown in Fig. 6.

The averaging time is connected to the frequency bands so that $BT_{av} \geq 1$ to obtain reliable results. This is a well-known condition for the analysis of stationary signals, but at the first glance it could seem to be difficult to meet in decay measurements. However, ensemble averaging offers a solution to the problem: using this technique, a requirement for the number of repeated and ensemble averaged excitations $N_{exc}$ should be

$$N_{exc} \geq \frac{1}{BT_{av}}.$$  \hspace{1cm} (5)

To minimize the number of excitations, the averaging time should be as large as possible but still fulfill conditions (3) or (4). Looking at these requirements, it is seen that a much larger averaging time is allowed for time-reversed analysis than for forward analysis. Hence fewer excitations are necessary, which is an additional feature of the time-reversed analysis. For the actual measurements $T_{av} = \frac{1}{28}$ s and $N_{exc} = 12$ were used for forward analysis, while $T_{av} = \frac{1}{16}$ s and $N_{exc} = 2$ were used for time-reversed analysis. An example of the analysis of one single excitation is shown in Fig. 7. It is noticed that the forward analysis shown in Fig. 7(b) is identical to the decay curve shown in Fig. 6(a).

2.4 Integrated Impulse Response Method

The integrated impulse response method is equivalent to the use of a very long averaging time. In this case it is not relevant to consider Eq. (5), and one excitation in each position is sufficient.

Spatial ensemble averaging can be made as described, that is, by averaging the decay curves from each position or, more practically, by averaging the squared impulse responses into an ensemble averaged impulse response, which is then integrated to yield the decay curve.

Fig. 6. Example of one-third-octave decay measurements using noise excitation and ensemble averaging (studio 21, 125 Hz). (a) Single excitation. (b) Ensemble average of 12 excitations in one position. (c) Spatial ensemble averaged decay curve using six source–microphone combinations; 72 excitations in total.

Fig. 7. Example of decay measurements using noise excitation (studio 21). (a) Time recording of interrupted broad-band noise. (b) Forward analysis of time recording, one-third octave, 125 Hz ($T_{av} = \frac{1}{28}$ s) (c) Reverse analysis of time recording, one-third octave, 125 Hz ($T_{av} = \frac{1}{16}$ s).
2.5 Limitations Caused by Sampling Time Interval

One of the advantages of exponential averaging is that it is possible to choose the time interval for sampling the decay curves \( t_{\text{samp}} \) independently from the averaging time. If at least \( n \) sample points are wanted for a regression line within the evaluation range \( D \), the condition is

\[
t_{\text{samp}} \leq \frac{T_{60}}{n} \cdot \frac{D}{60}.
\]

Typical values are \( D = 20 \text{ dB} \) and \( n = 3 \) (2 being the absolute minimum for \( n \)). For the actual measurements \( t_{\text{samp}} = 5 \text{ ms} \), which should make it possible to evaluate a range of \( D = 10 \text{ dB} \) for reverberation times \( T_{60} \geq 0.1 \text{ s} \).

3 INSTRUMENTATION

The measurements were carried out with the Brüel & Kjær real-time analyzer type 2133. A more detailed description of the use of this instrument for the measurement of short reverberation times is given in [10].

The averaging time of the detector has been chosen so that the lower limit for accurate reverberation times is 0.11 s in all the measurements. In order to meet requirement (5) at the lowest one-third-octave band of interest, 50 Hz, a total of 12 excitations in each position was used for forward analysis. Only two excitations were required for reverse analysis, because a longer averaging time could be used. The instrumentation is shown in Fig. 8.

A 6-mm pistol was used for impulse excitation in combination with a \(-6\text{ dB} per\) octave filter. The latter did improve the signal-to-noise level at low frequencies, and so the pistol was usable in a wide frequency range. The instrumentation is shown in Fig. 9.

Two source positions were used, one of them close to a corner with the center of the loudspeaker 0.4 m from each of the nearest surfaces. The pistol was fired in approximately the same positions.

Three microphone positions were distributed in each room, 1.0 m, 1.2 m, and 1.4 m above the floor. Each source position was used in combination with each microphone position, making a total of six combinations, which were used for spatial ensemble averaging. In each studio the microphone positions were identical for all reverberation measurements.

The noise excitations with forward analysis were made directly using the buffer memory of the instrument for holding the ensemble averaged multispectra, that is, decay curves, in parallel one-third-octave bands (see Fig. 10).

The noise excitations for reverse analysis and the impulse excitations were recorded as time signals (sampling time interval 11 \( \mu s \)) and stored on floppy disc for later analysis (see Fig. 11). The measurement setups used for reversed analysis are shown in Figs. 12 and 13.

4 MEASUREMENT RESULTS

Examples of measured decay curves in one of the studios at the 100-Hz one-third octave are shown in Fig. 14 for noise excitation and in Fig. 15 for impulse excitation.

The reverberation times are evaluated from the spatial ensemble averaged decay curves using linear regression within an evaluation range of 20 dB starting 5 dB below the top of the decay curves. At 50 and 63 Hz the signal-to-noise level was not sufficient in some of the measurements, so all results at these frequencies are omitted.
even if an evaluation can be made using a range smaller than 20 dB.

The measured reverberation times in the studios are shown in Figs. 16 and 17. Compared with the limits discussed, it is seen that only the values based on time-reversed analysis are reliable at the lower frequencies (below about 500 Hz). There is a clear tendency that when the requirements for the forward analysis are not met, the results are longer than those from the time-reversed analysis.

It appears that the two methods of excitation, interrupted noise and integrated impulse response, agree very well.

Comparing the results from the two studios [Figs. 16(b) and 17(b)], it is seen that studio 21 has a bass rise, which is not found in studio 8. This must be a result of the differences in the acoustic treatment of the studios, as described in Sec. 1. The reverberation times of the two studios are more easily compared looking at Fig. 18 (only results using the integrated impulse response method are shown). Fig. 18(a) gives the results of the forward analysis and Fig. 18(b) the results of the time-reversed analysis. Fig. 18(a) shows

Recording of time signal

Storage on disc

Analysis of time signal (time reversed)

Inspection of decays on screen (may be omitted)

Calculation of reverberation time

The procedure may be automated using autosequences (programmed keypushes)

Fig. 10. Main steps for measurement of reverberation time using B & K type 2123/33.

Fig. 11. Main steps for measurement of very short reverberation time using B & K type 2123/33.

Fig. 12. Measurement setup used at reversed interrupted noise measurements in talks studios. Slice shows an averaged decay at 500 Hz.

Fig. 13. Measurement setup used at reversed integrated impulse response measurements in talks studios. Slice shows an averaged impulse response at 500 Hz.
measurement results, which at low frequencies are far below the lower limit for reliable results. Consequently, an evaluation of the constructions cannot be based on these results. However, the results from the time-reversed analysis [see Fig. 18(b)] are reliable (for further explanation, see Sec. 2.1), and thus the differences in results may be trusted and attributed to differences in reverberation times.

In both studios the lower natural frequencies have been calculated, and the number of axial, tangential, and oblique modes are as shown in Table 1.

5 CONCLUSION

The measurement results from two talks studios have demonstrated that the ringing of one-third-octave filters can introduce errors in the reverberation times evaluated from the decay curves. These difficulties can be overcome when a time-reversed analysis is used. In addition this method allows the number of excitations at each position to be reduced considerably if the interrupted

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Fig. 14. Interrupted noise excitation in studio 8; 100 Hz, one-third-octave band. (a) Ensemble averaged decay curve using six source-microphone positions and forward analysis; 72 excitations in total. Requirement (1) is not met. (b) Ensemble averaging as in (a), but using time-reversed analysis; 12 excitations in total. All requirements are met.

Fig. 15. Impulse excitation in studio 8; 100 Hz, one-third-octave band. Same positions as in Fig. 14. In both examples decay curve (solid curve) has been calculated by backward integration of impulse response (bar graph). (a) Ensemble averaged impulse response and corresponding decay curve using six source-microphone positions and forward analysis. Requirement (1) is not met. (b) Ensemble averaging as in (a), but using time-reversed analysis. All requirements are met.

Fig. 16. Measured reverberation times in studio 21 using noise and impulse excitation. Results are compared with lower limits for reliable results, Eqs. (1) and (3) for forward analysis, Eqs. (2) and (4) for time-reversed analysis. — using interrupted noise; ··· using integrated impulse response; — lower limit for reliable results. (a) Forward analysis. (b) Time-reversed analysis.

Fig. 17. Measured reverberation times in studio 8 using noise and impulse excitation. Results are compared with lower limits for reliable results, Eqs. (1) and (3) for forward analysis, — using interrupted noise; ··· using integrated impulse response; — lower limit for reliable results. (a) Forward analysis. (b) Time-reversed analysis.
noise method is used.

It has been demonstrated that the interrupted noise method and the integrated impulse response method agree very well and that both methods can benefit from the time-reversed analysis when very short reverberation times have to be measured.

Comparing the different acoustic treatments of the two studios, it is concluded that the complex treatment with a total depth of only 100 mm on the walls of studio 21 gave a moderate bass rise of the reverberation time, although the acoustic ceiling was suspended 0.5 m. In studio 8 the acoustic ceiling was not suspended as much, but the treatment on the walls was thicker and with a larger air space and a supplementary low-frequency panel absorber behind, which gave a reverberation time without any bass rise within the measuring range of 80 Hz to 8 kHz. This difference between the two studios could not have been found if traditional forward analysis of the decays had been used.

6 REFERENCES


Table 1. Calculated number of natural frequencies in two studios, valid for five lowest one-third-octave bands.

<table>
<thead>
<tr>
<th>Center Frequency (Hz)</th>
<th>Studio 21</th>
<th>Studio 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Axial</td>
<td>Tangential</td>
</tr>
<tr>
<td>80</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>4</td>
</tr>
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<td>125</td>
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<td>14</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

THE AUTHORS

Birgit Rasmussen was born in Denmark in 1949. She obtained an M.Sc. degree in civil engineering in 1973 from the Technical University of Denmark. From 1973 to 1986 she worked at the Danish Acoustical Institute, which is associated with the Academy of Technical Sciences and situated at the Technical University of Denmark. One main area of her work consisted of building acoustical laboratory measurements requested by the Danish building material manufacturers for the development and authorized testing of building components. In addition, a number of experimental research projects were carried out, primarily related to test methods or sound insulation of windows, e.g. investigation of the influence of glass thicknesses, lami-
nation, glass spacing, and gas filling in sealed double
and triple glazing. Another field of work was participa-
tion in working groups developing or revising stan-
dardized building acoustical test methods.

Since 1986, Ms. Rasmussen has been employed by
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Jens Holger Rindel was born in Copenhagen,
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a Ph.D. in acoustics in 1977, both from the Technical
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His teaching activities involve courses on funda-
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room acoustics, and integrated courses on design
methods in architectural acoustics, with emphasis on
cooperation between engineers and architects. His re-
search activities began with theoretical and experimental
work on sound insulation. Other research topics include
acoustic modelling techniques, reflection of sound from
curved surfaces, diffraction effects of single reflectors,
and reflector arrays. Recently his work has concentrated
on room acoustic computer models and the development
of integrated systems for building design. Another topic
of interest is acoustic measuring methods. Dr. Rindel
is a member of the working group for revision of the
standard for measuring reverberation time ISO 3382.
He has also done some consultancy work, including
the development of a new open telephone box for the
City of Copenhagen and the development of new sound
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in the renovation of the concert hall of the Danish
Broadcasting Corporation in Copenhagen.

Helge Henriksen was born in Copenhagen, Denmark,
in 1934. He received an M.Sc. degree in electronic
engineering from the Technical University of Denmark
in 1964.

That year he joined the Acoustics Laboratory of the
Technical University of Denmark working on the cal-
ibration of laboratory standard microphones and the
investigation of organ pipes.

Since 1967 he has been involved with room and
building acoustics and loudspeakers in the Danish
Broadcasting Corporation.