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The influence of profiled ceilings on sports hall acoustics: ground effect predictions and scale model measurements.

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Abstract

Over the last few years, reverberation times and sound pressure levels have been measured in many sports halls. Most of these halls, for instance those made from stony materials, perform as predicted. However, sports halls constructed with profiled perforated steel roof panels have an unexpected very low reverberation time in the 125 and 250 Hz octave bands. The aim of this study was to provide an explanation for this low-frequency anomaly. A 1:20 scale model of a sports hall was constructed and placed in a small anechoic chamber. The roof could be equipped with differing ceiling types: a flat non-absorbing ceiling, a flat absorbing ceiling, two different profiled non-absorbing ceilings and a profiled absorbing ceiling. With a spark sound source and a small microphone, the impulse-response of the scale model could be registered and analysed. Moreover, a Matlab model was constructed to simulate the acoustic behaviour of the sports hall. This model included the 'ground effect' of the roof surface, an effect typically not included in commercial ray-tracing programs. The measurements and the simulations showed that the high sound absorption values of a perforated panel roof structure at 125 and 250 Hz can be (partly) explained by its shape. The diffusing properties of the corrugated roof have an effect similar to sound absorption. Because the roof is the largest absorbing surface in a sports hall, this effect can have a significant effect on the low-frequency reverberation time.

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1. Introduction

In 2010, teachers and employees of a sports hall in Rijssen-Holten in The Netherlands got publicity because of a protest action where all students were wearing earmuffs while conducting sporting activities. By this action, the employees tried to get attention for the bad acoustics in sports halls which, in their opinion, is the cause of their hearing problems. The KVLO, the 'Koninklijke Vereniging voor leraren Lichamelijke Opvoeding' started a survey among PE teachers to find out whether there were complaints or not. This survey resulted in about 250 complaints possibly related to the acoustics in sports halls. Most complaints were: throat problems, tiredness and hearing problems. Uittenbosch [1] indeed found that in many sports halls the sound pressure level is too high during sports activities.

Over the last decade, several other studies into the acoustics of sports halls have been conducted in the Netherlands, [2], [3], [4], [5], [6], [7], [8]. These studies mainly focussed on the reverberation time as a parameter for characterising the quality of a sports hall. The authors share the same conclusions. The reverberation time is not a suitable quantity to be used as a standard for acoustics in sports halls. Although it is a very constant and easy to measure parameter, it is not always true that a sports hall that exceeds the limit has bad acoustics. Though, the other way around, if a sports hall stays within the limits, the acoustics is generally good. Furthermore, the sound field in a sports hall is not diffuse because most sound absorbing material is placed on the ceiling, so for example (flutter) echoes could have a big influence on reverberation time measurements in practice. This absorption is not often questioned. Absorption coefficients of materials are measured in laboratory situations under assumed diffuse field conditions [9]. These values are normally assumed to be right. However, sports halls typically do not have such sound fields.

Bad acoustics in common sports halls may relate to an uneven distribution of the sound absorbing material. Often, the ceiling absorbs most of the sound while the floor and walls up to at least 3 metre reflect most of the sound. Therefore, the vertical sound field is absorbed faster than the horizontal sound field. This causes concave Schroeder curves and may result in ill-defined reverberation times. Furthermore, after a short time, this also leads to grazing incidence of sound on the ceiling. Such highly angled incidence also creates changes in the sound absorption behaviour as compared to the random sound incidence measured in a reverberation room. As we also know from auditoria and concert halls, grazing sound incidence over the audience is responsible for the so-called seat dip effect [10], [11], [12]. Although the precise causes for the seat dip effect are yet to be fully understood, similar behaviour may be acting in certain types of sports halls with absorbing perforated steel ceilings.

Besides the problem of long reverberation times, another problem is found in sports halls. Measurements show that halls constructed with stone-like materials absorb sound according to the expectations based on the material properties. However, sports halls constructed with sound absorbing perforated steel wall and/or ceiling panels seem to absorb the low frequency sound better than expected from octave band laboratory measurements. Figure 1 shows the common behaviour of the reverberation time in a sports hall. It decreases with increasing frequency. Figure 2 shows a low reverberation time at 125 and 250 Hz. These measurements were conducted by the consultancy LBP/Sight based on the measurement protocol of ISA sport for sports halls [13].

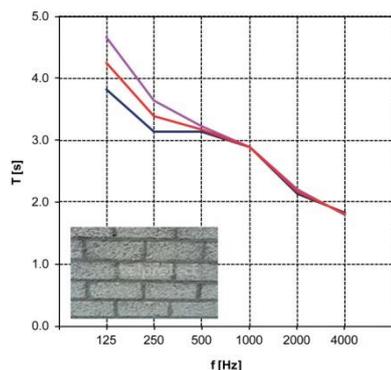


Figure 1 - Reverberation time T20, measurement results in sports halls constructed with stone-like materials. Source: LBP|Sight

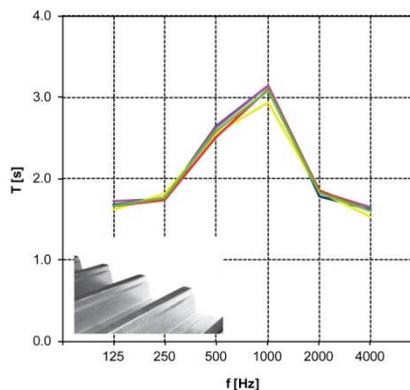


Figure 2 - Reverberation time T20, measurement results in sports halls constructed with perforated steel panels. Source: LBP|Sight

During this research laboratory tests have been performed on the absorption coefficient of SAB perforated roof panels in different setups, see figure 3. The octave band results do not show any deviant values. The 1/3rd octave band results though, show an increase of sound absorption in the lower frequencies around 80-100 Hz, as shown in figure 4. The reason for this larger absorption coefficient needs to be found in the mineral wool layer since the peak is also visible in the results of setup 'ISO'; the setup without steel panels. The effect of this higher absorption coefficient contributes to the low reverberation times in the measured sports halls (figure 2) but cannot fully explain the found deviation.

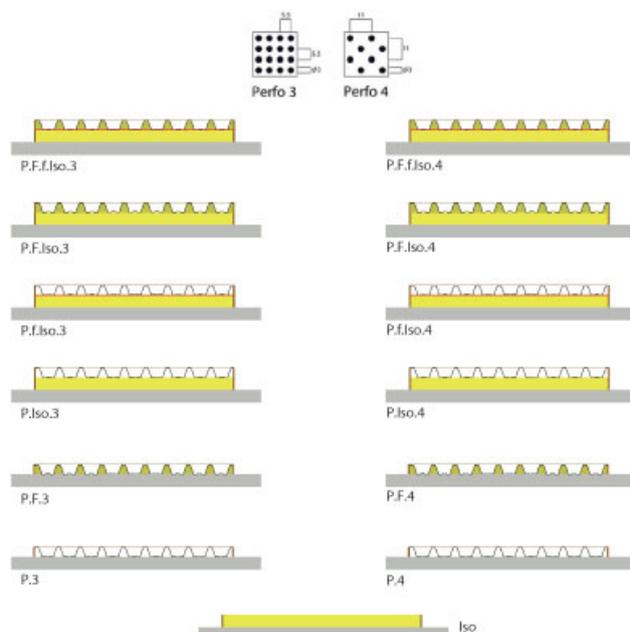


Figure 3 – Laboratory measurement setup. In yellow Rockwool Rhinox 110 mm, in green rockwool profile filling packed in a vapour barrier 30 kg/m^3 .

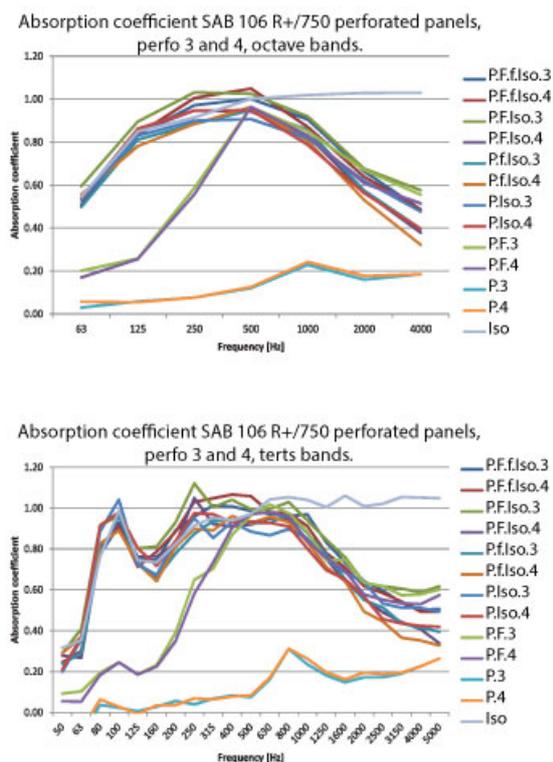


Figure 4 – Laboratory measurement results in octave bands (top) and 1/3rd octave band (bottom).

Nevertheless, the aim of this study was to find the cause for the low frequency deviation in the reverberation time of sports hall with perforated steel panels. In order to find an answer to this, the following hypothesis was tested in a scale model:

‘The sound absorbing behaviour of a perforated steel panel in a constructed sports hall differs from its behaviour in a laboratory because the shape of the panel in combination with the non-diffuse sound field results in apparent sound absorption of parallel striking sound based on the phase shift principle.’ [14]

The use of scale models for investigating the acoustics of auditoria already has a long tradition dating back to 1934, the 1960s, 1970s and 1980s [15] [16] [17] [18] [19]. Also other types of rooms, like landscaped offices [20] and factories [21] [22] have been subject of scale model studies. For outdoor purposes, the effectiveness of acoustic barriers has extensively been researched in scale models [23] [24] [25]. Kleiner et al. [25] even discuss the possibility of using acoustic scale models for auralisation. Already in the 1990s, the use of physical scale models as part of the design and engineering process of acoustically sensitive spaces was well-established [26]. Recent developments mainly involve improvements of the hardware used for the measurements, like small sound sources [27]. The advantages of scale model tests are that acoustic phenomena which are sometimes difficult to simulate in room acoustics software, like diffraction and echoes, can relatively easily be detected. Since this study focusses on scattering effects and the ground effect, a scale model is an ideal tool for this investigation.

2. Background theory: the ground effect

When sound travels above a surface – low grass for instance – sound levels increase or decrease compared with real free field propagation. This is called the ground effect. This effect depends on the distance between source and receiver and on the impedance of the surface, which in turn depends on the sound frequency. The ground effect (in decibels) results from interference between two

sound waves: the sound travelling directly from source to receiver and the sound reflected from the ground. Its effect is stronger if the source and the receiver are close to the ground [28], [30]. The ground effect consists of both the absorption of the sound by the ground surface and the reduction of sound due to a phase shift between direct and reflected sound waves [31]. Because the ground effect involves interference, the sound pressure at one receiver position can both be enhanced or attenuated. In this article, the ground effect might also be called ‘the ceiling effect’ since the effect mostly takes place after a reflection from the ceiling surface of a sports hall. Ray tracing in any case does not consider this ground effect.

In case of normal incidence of sound waves or in case of locally reacting surfaces, the surface’s properties may be represented by its normal-incident surface impedance (Z). An acoustically perfectly hard surface has infinite surface impedance whereas an acoustically perfectly soft surface has an impedance equal to the specific acoustic impedance of air, ρc .

In case of externally reacting surfaces, more information is required to characterise the surface. A pulse, produced by sound source S is received by microphone M (figure 5). The received sound consists of the direct sound (black, red in the coloured version) and the reflected sound (gray, blue in the coloured version). The reflected sound can also be considered as coming from an imaginary source S' . A part of the incident sound wave is absorbed by the material. Besides, the phase of the reflected sound wave is different from the phase of the incident sound. The sound pressure in M resulting from both the direct and reflected sound wave can be written as [16]

$$p(x, y, z) = p_0 \left(\frac{e^{-ikr_1}}{4\pi r_1} + Q \frac{e^{-ikr_2}}{4\pi r_2} \right) \quad (1),$$

In this equation, p is the sound pressure, p_0 is the amplitude of the sound pressure (if only the direct sound is considered), k is the wave number [m^{-1}], r_1 is the direct distance between the sound source and the microphone and r_2 is the distance between the mirror source and receiver (figure 5). It is important to realise that this equation also contains a time component $e^{i\omega t}$. We did not include that in the equation above because here only the spatial component is relevant.

Q is the spherical wave reflection coefficient of the surface which is calculated from

$$Q = R_p + (1 - R_p)F(Z, k, \alpha, r_2) \quad (2),$$

With R_p [-] being the plane wave reflection coefficient and $F(Z, k, \alpha, r_2)$ the ground wave or the boundary loss factor. This second term of Q corrects for the fact that when the source is close to the surface the sound waves are not planar but spherical.

The previously mentioned phase shift effect is represented by this Q -value since it influences the sound pressure of the reflected part of the sound wave. If a surface is perfectly non-absorbing, F equals 1 and thus Q equals 1. In all other cases it varies as a complex number between 1 and -1. Q depends on the following variables: the angle of incidence (α), the wave number (k), the distance from imaginary source S' to microphone M (r_2) and the normal-incident surface impedance (Z).

The plane wave reflection coefficient can be calculated from:

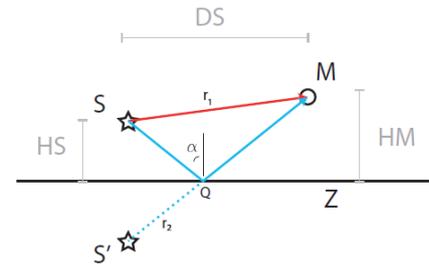


Figure 5 – Direct and reflected sound.

$$R_p = \frac{Z \cos(\alpha) - \rho c}{Z \cos(\alpha) + \rho c} \quad (3),$$

When a sound wave strikes the surface, so-called grazing incidence ($\alpha \approx 90^\circ$), this plane wave reflection coefficient will be -1. Acoustically hard surfaces, like the floor of a sports hall, have very high impedances; so, Z tends to infinity, and hence, R_p tends to 1. In this case, formula (2) leads to $Q = 1$ and equation (1) fully depends on the phase shift between r_1 and r_2 . This is the simple form of interference.

For perfectly absorbing materials, the impedance Z tends to ρc . At first sight one might expect that the reflection vanishes ($Q = 0$ in equation (1)), but a close look at equation (3) illustrates that this is not the case since then

$$R_p = \frac{\cos(\alpha) - 1}{\cos(\alpha) + 1} \quad (4),$$

and $R_p = 0$ for normal incidence ($\alpha=0$) only. R_p tends to -1 for nearly grazing incidence. Hence it is often called the “ground wave”. Now the term F in equation (2) becomes very important for grazing incidence. If it is omitted, the value of Q becomes -1 at grazing incidence and low frequency sound would disappear. F has the following properties:

- It depends on the angle of incidence. F has its largest influence when α tends to 90° . For normal incidence ($\alpha = 0^\circ$), F vanishes completely.
- F depends on the distance between the mirror source and the receiver.
- F depends on the impedance of the surface, and as such on the frequency. Many absorbers are not absorbing at low frequencies, while absorption tends to 100% at higher frequencies.

This all leads to $Q = 1$ for low frequencies and $Q = R_p$ for high frequencies. The influence of F on the low frequency behaviour of equation (2) is shown in figure 7.

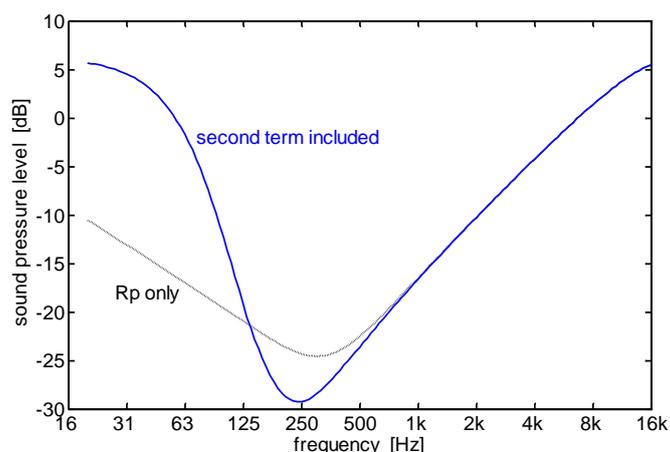


Figure 7 - The influence of the second term in equation (2) on the low frequency behaviour. The dotted line shows Q without the second term, the full line includes the second term. Calculations are made with $\alpha = 89^\circ$ and $r_2 = 115$ m. Z is calculated with the model of Delany and Bazley [31] with a flow resistivity of $1.0 \cdot 10^4$ Ns/m⁴.

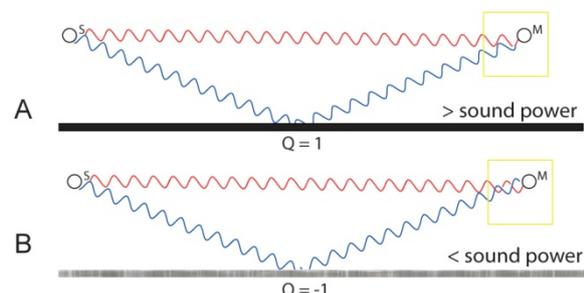


Figure 6 – Increase or decrease of sound power caused by interference.

The method of the calculation of the ground effect is described by Attenborough [29], the calculations are done with a model proposed in 1980 by Attenborough et al. [30]. The calculation of the impedance Z is based on the model of Delany and Bazley [31]. This model is a one parameter model for fibrous absorbing materials; it is generally considered relatively inaccurate for ground surfaces [32]. However, in this paper the ceiling of a sports hall is considered which contains at its basis mineral wool insulation.

Furthermore, in the past there have already been a few studies that looked into the effect of surface profiles on the ground effect and how the sound pressure levels near these surfaces are changed as compared to flat surfaces [33] [34] [35] [36] [37]. When a near-grazing sound wave hits a profiled surface, surface waves are created. The result of this is that at low frequencies and close to a profiled surface the sound pressure level may be higher than close to a flat surface. Generally, these studies found that in case of rectangular profiles the created surface waves are stronger than in case of trapezoidal profiles; hence, the near-grazing effect is stronger for rectangular profiles. Similar results were also found in the study of the present paper. Furthermore, the mentioned studies showed that this near-grazing effect can be represented by an effective impedance corresponding to low flow resistivity. This latter finding also corresponds with a finding in the present paper in which a material with low flow resistivity better represents the effect of profiled surfaces as compared to a material with a large flow resistivity.

3. Methodology

In acoustical design, scale models make it possible to study phenomena like scattering, diffraction and propagation over absorbing surfaces. The big attraction of scale models is that the mentioned phenomena behave on scale. However, for a model scale 1:20, the frequencies used in the scale model need to be multiplied by a factor 20, so special acoustical equipment for high frequencies is needed.

3.1 Measurement setup

To investigate the influence of different shaped roof structures, different profiled panels are used during the measurement. The testing material in figure 8 refers to profiles A, AA, B, BB and C. Profile A has a flat surface, created from one painted MDF plate (figure 8). Profile B has a ribbed surface with perpendicular slots, created from a milled and painted foam board. Profile C has the shape of a 'real' roof structure which dimensions are based on the size of SAB panel type 106+/750. Additional sound absorbing material is added to profile AA and BB. A thin (2 mm) layer of fleece is used for profiles B and BB. The fleece in profile BB imitates the sound absorption in the fluting of the perforated steel panels.

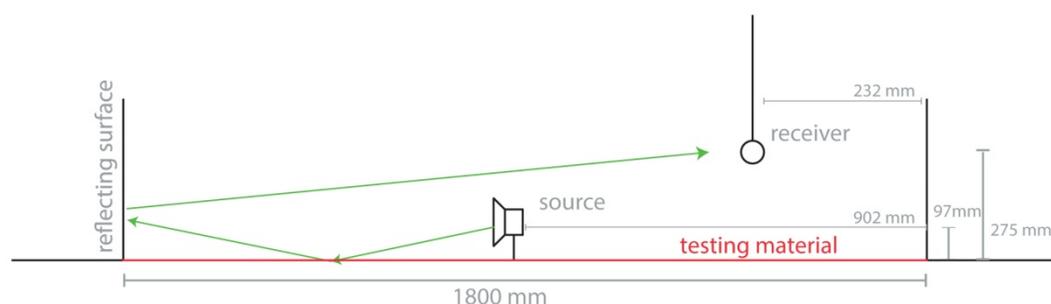


Figure 8 – Test method scale 1:20. The scale model is used upside-down with the ceiling on the floor. The walls can be easily added together with, if necessary, the floor on top of the model.

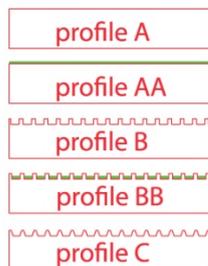


Figure 9 – Tested profiles.

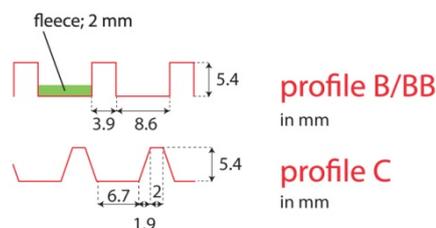


Figure 10 – Dimensions of ribbed surfaces.

The used scale of the model is 1:20. The (interior) model size is: 1200 x 1804 x 350 mm³. This corresponds to a sports hall of 24 x 36 x 7 m³. The NOC*NSF standard [38] gives a maximum reverberation time of 1.5 seconds for sports hall type B3. This type includes sports halls of 32 x 28 m. The measurements are done in a small anechoic chamber of TU Delft's faculty of Applied Sciences to prevent unwanted reflections that would disturb the measurements.

3.2 Measurement equipment

The used sound source is a homemade spark source. The produced sound is a sound pulse evacuating from an spark caused by a discharged condenser. Since the scale of the model is 1:20 and the frequencies of interest are low, the used frequencies during the measurement range from 500 Hz to 100 kHz, or 25 Hz to 5 kHz in real scale.

The used receiver is a 1/8" microphone, type 4136 Brüel & Kjaer. The distance between the sound source and receiver is about 720 mm, which is enough to distinguish the direct from the indirect sound pulses.



Figure 11 – Used spark source.

3.3 Interference pattern

Figure 13 gives the measurement results of the model with two reflecting walls and a ceiling surface. The first peak at 0 ms in the echogram shows the sound pressure of the direct sound. The following peaks show the sound pressure of reflected pulses. Figure 14 shows spectra for the combinations of direct sound and a single floor reflection. For this graph, the reflected pulse after 6.3 ms is used. The different lines are comparable and independent from the source pulse¹.

The graph shows interference dips that occur in regular sequences, marked with arrows. This is an interference pattern. The frequencies where interference dips occur depend on the difference in distance travelled by the direct and reflected sound pulse and on the ground effect.



microphone.

The interference frequencies can be calculated with equation 4. Equation 5 gives an approximation, it only applies when $DS \gg HM/HS$.

The interference frequencies can be calculated beforehand. In our measurement set-up, $DS = 72$ cm, $HS = 9.7$ cm, $DS = 14.6$ cm. When the reflection takes place after 6.3 ms, the interference frequencies (minima) will be: 17 kHz ($n=1$), 52 kHz ($n=3$), 87 kHz ($n=5$).

$$f = \frac{(2n-1)c}{2(r_2 - r_1)} \quad (4),$$

¹ The scale model measurements are done with a spark as sound source. This spark is never the same. The lines in the graph can be used to compare different results from different measurements because they show the difference of the spectrum of the spark and the spectrum of the sound at the receiver.

With:

$(r_2 - r_1)$ = Path length difference between direct and reflected sound waves

c = propagation speed = 343 m/s

$$f = \frac{n \cdot c \cdot DS}{4 \cdot HS \cdot HM} \quad (5).$$

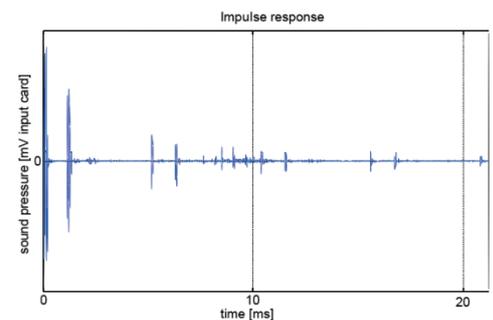
With:

$n = 0, 2, 4, 6, 8, \dots$ for maxima

$n = 1, 3, 5, 7, 9, \dots$ for minima

HS, DS and HM: see figure 5.

The measurement results are also visualized in Schroeder curves, as shown in Figure 15. Schroeder curves are integrated impulse responses derived from echograms. When measuring the reverberation time in a 'real' sports hall, a comparable method is used. Schroeder curves give useful information on the absorbing behaviour of tested materials. The position of the line at $t < 0$ along the y-axis provides the total acoustic energy received by a receiver; the lines for $t > 0$ show the decrease of acoustic energy in the room as function of time. The sound absorbing properties of the room for each octave band can be seen from two things. If more sound absorption is present inside the room, the total energy in the room is lower meaning the line for $t < 0$ crosses the vertical axis at a lower value. Furthermore, if more absorption is present, the sound decays faster meaning the slope of the line for $t > 0$ is steeper



4. Results of measurements with two walls and a ceiling

In figure 13, an example is given of the direct sound and the various reflections. They are clearly separated in time due to the differences in travel times that occur in a model with only two walls like in figure 7. The differences in spectra between the direct sound and the reflection after 6.3 ms for profiles A, AA and B are shown in figure 14. The interferences, are clearly visible in the graphs. For profile A, the calculated interference frequencies of 17 kHz, 52 kHz and 87 kHz (850 Hz, 2600 Hz and 4350 Hz in a real size sports hall) closely correspond to the measured interference frequencies.

Figure 13 – Impulse response with measured impulses and reflections in a setup with two walls and a ceiling.

When comparing the figures of profile AA and B to A, it is clearly visible that interference shifts to lower frequencies. Both the profiles AA (absorbing surface) and B (profiled reflective surface) behave in a similar way, although profile B is made from a non-absorbing material. This frequency shift shows the ground effect.

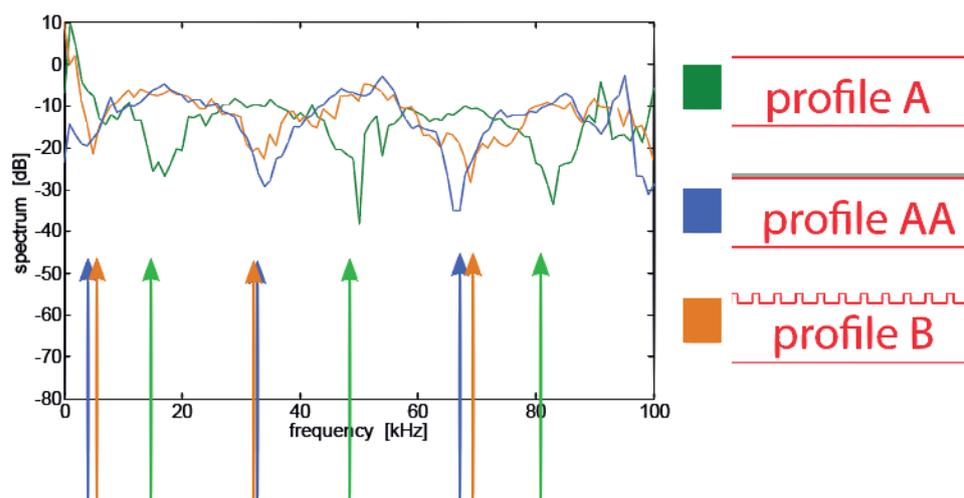


Figure 14 – Spectra of pulses and reflections with interference pattern.

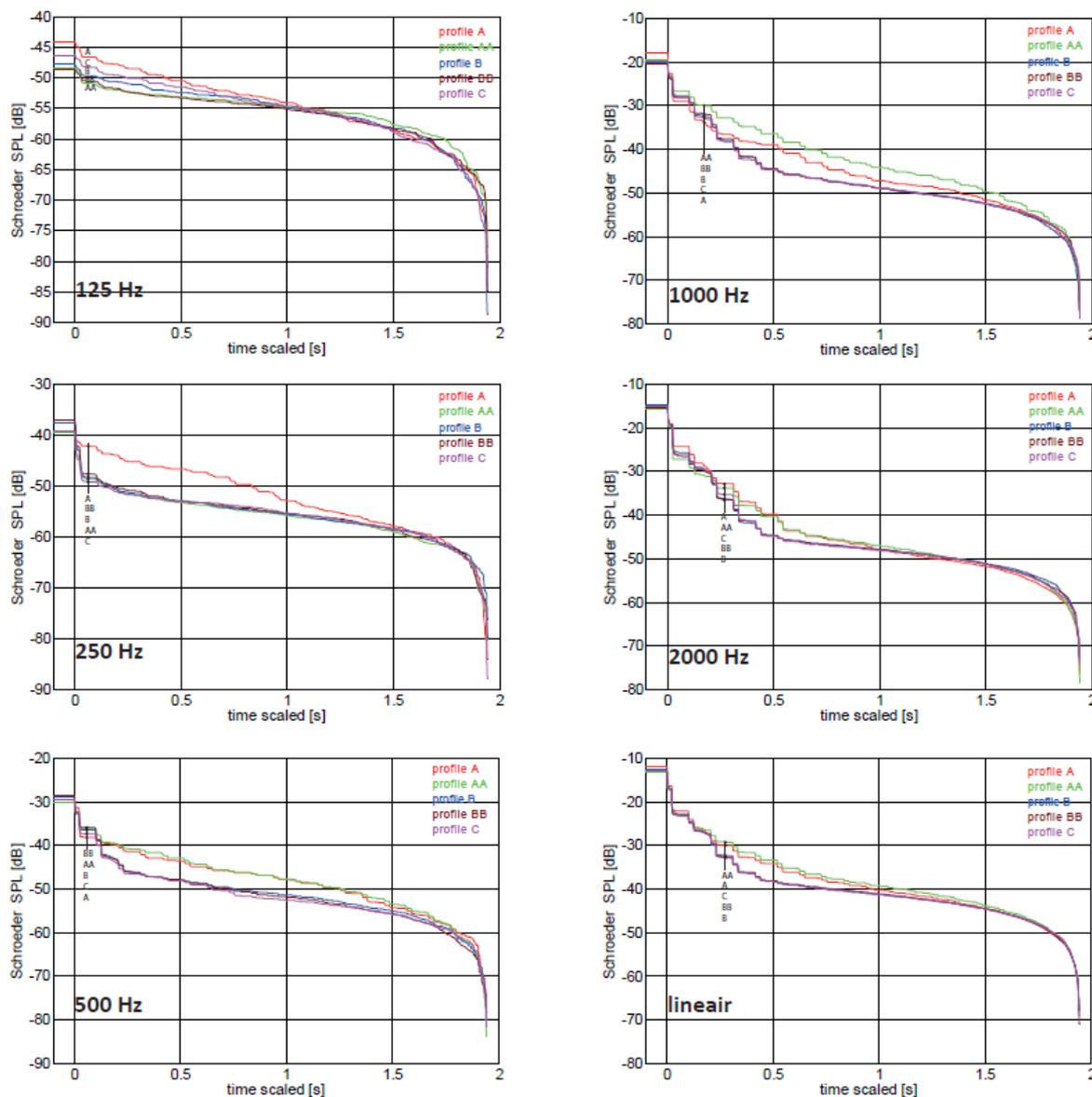


Figure 15 – Schroeder curves of measurements of situation with two walls and a roof with different profiled roofs per octave frequency band.

Figure 15 presents the Schroeder curves of the scale model measurements per frequency band for each of the five measured ceilings in one graph. These results show the profiled structures cause a considerable decrease in local sound pressure compared to a reflecting flat surface (profile A). This decrease is largest for the frequencies of 125 and 250 Hz. In the scale model, the effect of sound absorption and ‘sound absorption by shape’ is therefore mainly found for low frequency sound. It is not only visible from observing the slope of the reverberant decay, but becomes discernible from the echograms and Schroeder curves. Besides this, more things are striking:

1. The order of the lines (from high to low sound pressure level) generally is the same for most of the graphs. This means that profile A (reflective facing) absorbs least and profile BB and profile AA (both absorbing) absorb most of the sound. Besides, profile C absorbs less sound than profile B (both profiled).
2. The effect of scattering by the profiled shape is comparable to the effect of absorption by the fleece layer.

3. All curves show a concave character, except for the 125 Hz lines which are about straight. These curves can be expected in the almost one dimensional model of figure 7.

5. Results of theoretical study

The impulse response from the scale model was also simulated theoretically using a ray tracing model built in Matlab. The model is very simple as it only includes a roof and two side walls. The side walls are considered as perfect reflectors (no diffusion) and they are infinitely large, so the influence of the edges is not considered. For each reflection (like in figure 12) the ground effect is calculated from the source and microphone height and the (varying) distance between them. As said earlier: the ground effect is calculated with the model proposed by Attenborough et al. [30].

From the impulse response at one microphone position a Schroeder curve can be calculated, representing the reverberation curve.

Figure 16 shows the Schroeder curves for the measurement setup with $HM = 2,92$ m (real size). In figure 17, the same curves are shown for $HM = 8,76$ m which more closely corresponds to a real situation in a sports hall. The gray line (middle line in black and white version) shows the power curve. The green line (top line in black and white version) shows the effect of an acoustically hard surface (flow resistivity = $9,9 \cdot 10^9$ Ns/m⁴). The blue line (bottom line in black and white version) shows the effect of an acoustically absorbing surface like mineral wool (flow resistivity = $1,0 \cdot 10^5$ Ns/m⁴). When comparing the measured curves in figure 15 to the theoretical curves in figure 16, great similarity can be found. Figure 15 shows a decrease of the sound pressure level for 250 Hz and 125 Hz for profiled surfaces. This decrease can also be found in figure 16.

As mentioned before, the angle of incidence is very important when calculating the Q value. A theoretical approach of the ground effect for a sports hall, results in figure 18. This figure shows the sound pressure at one point, caused by direct sound and a reflected pulse at distances of 50, 100, 150, 200 and 250 m between source and receiver. The left graph shows a strong decrease for 250 Hz for the bigger distances. In the right graph, this decrease shifts to 125 Hz. A difference between the two figures is the height difference between the receiver and the ceiling (HM), left: 2,92 m, right: 8,76 m. The free height above the receiver in a real size sports hall comes close to 8,76 m. In the measurement setup (scale model), this height comes close to 2,92 m. With a bigger angle of incidence, the effect thus shifts to lower frequencies. Therefore, the ground effect should reduce the sound pressure of low frequency sound (125 Hz) in a sports hall with a profiled perforated roof structure.

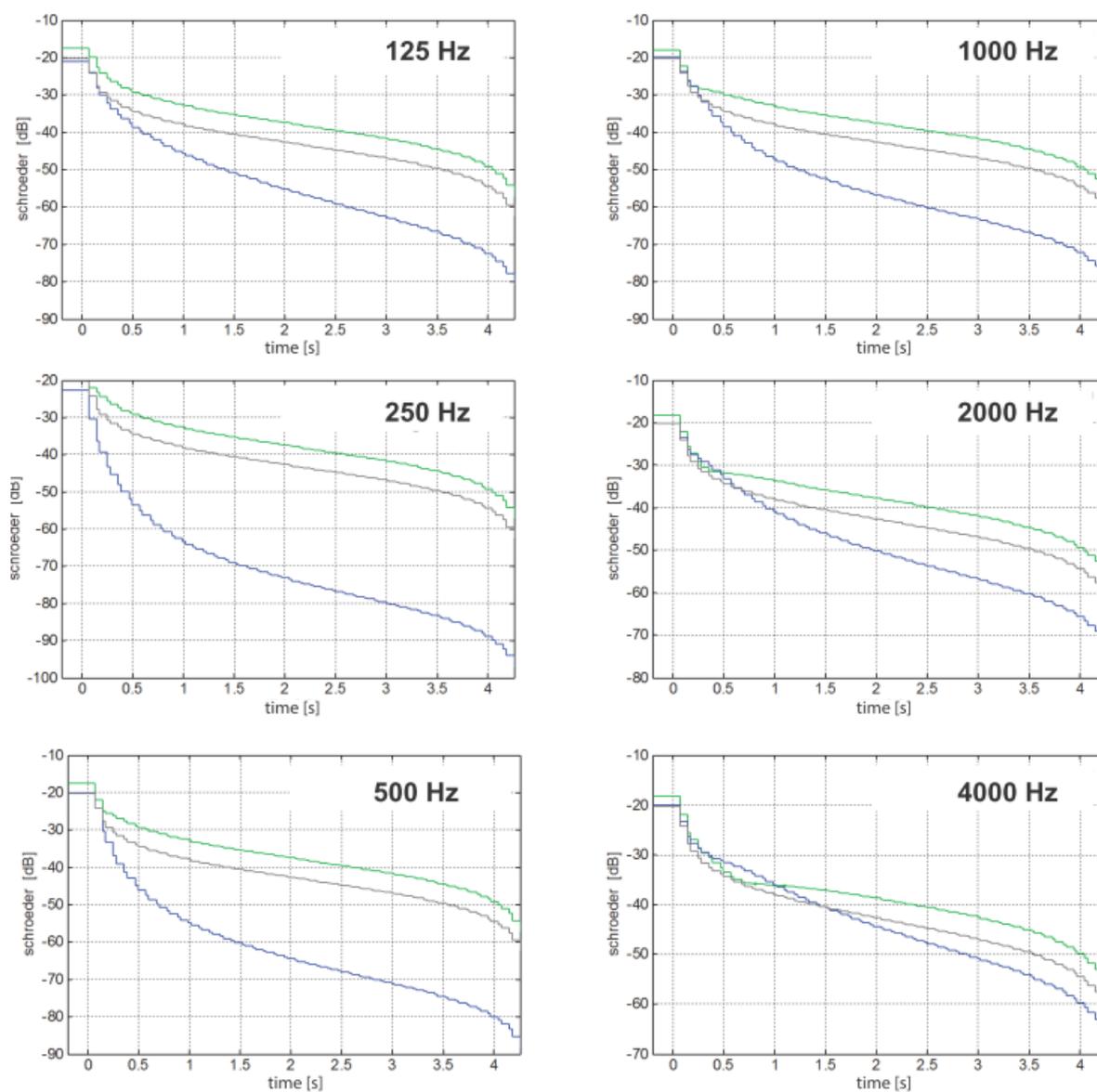


Figure 16- Theoretical Schroeder curves of situation with two walls and a roof with $HM = 2,92$ m and $HS = 1,94$ m (real size, comparable to measurement setup). Results per octave frequency band. Grey: the power curve. Green: the effect of an acoustically hard surface. Blue: the effect of an acoustically absorbing surface.

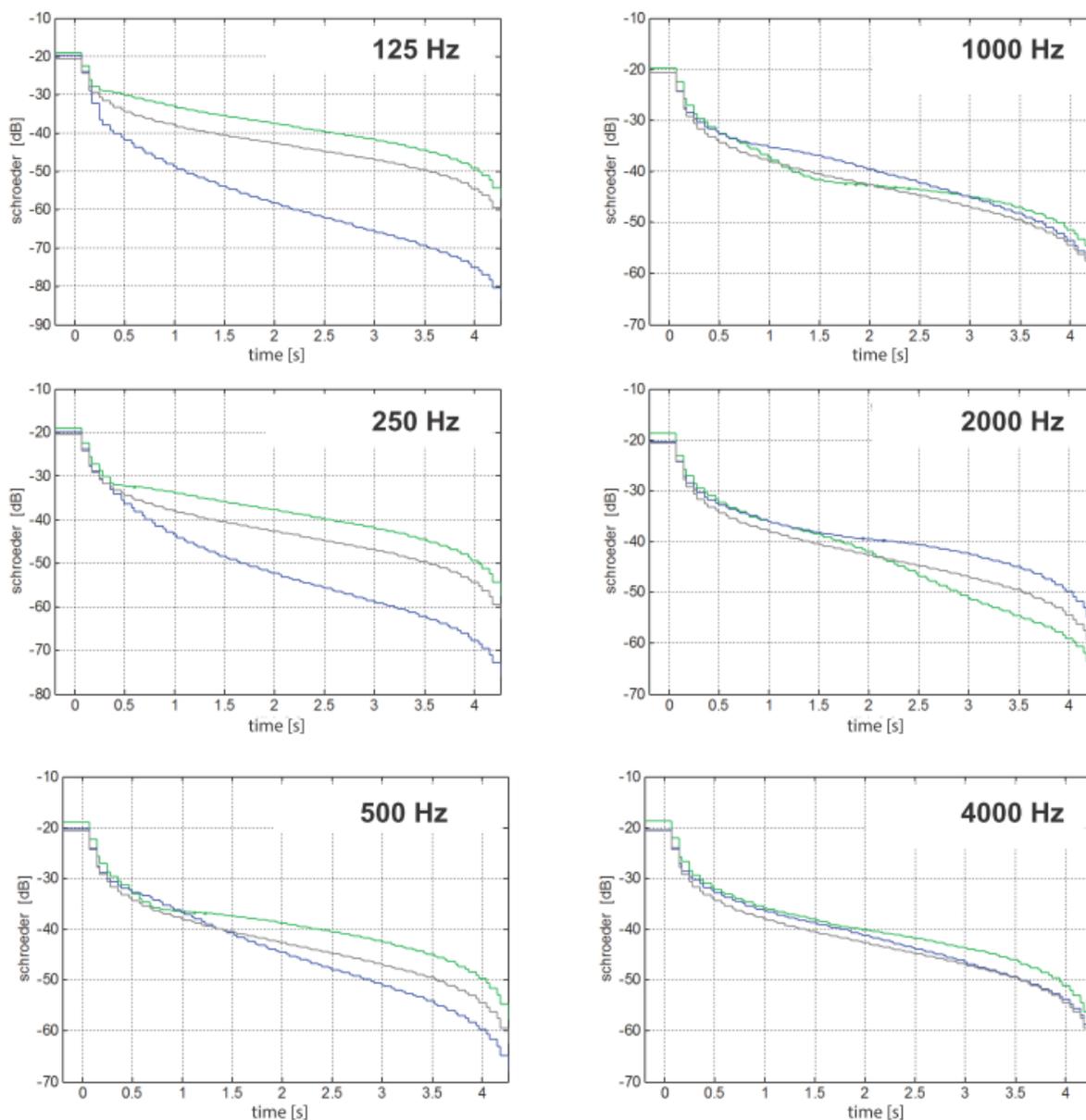


Figure 17 - Theoretical Schroeder curves of situation with two walls and a roof with $HM = 8,67$ m and $HS = 1,94$ m (real size). Results per octave frequency band. Grey: the power curve. Green: the effect of an acoustically hard surface. Blue: the effect of an acoustically absorbing surface.

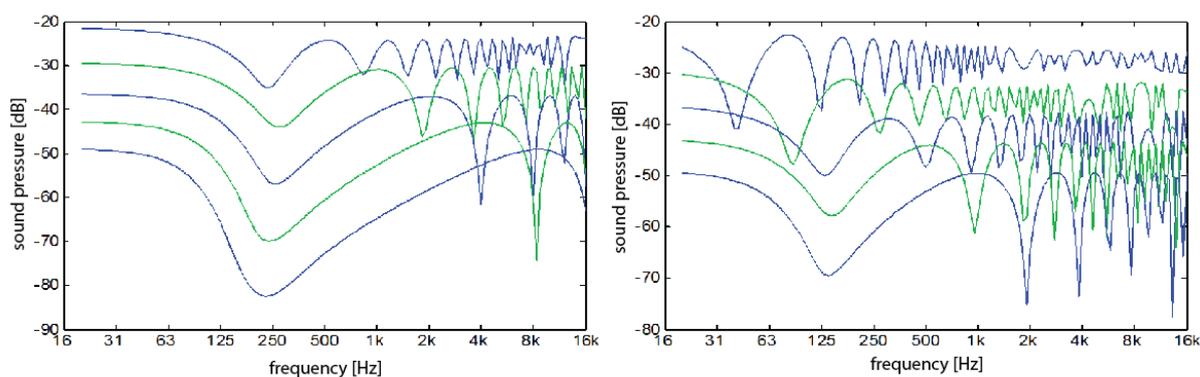


Figure 18 – Sound pressure level at receiver for $HM = 2,92$ m (left) and $8,76$ m (right) for different

distances between source and receiver ($HS = 1,94$ m). The line at the top represents 50 m; each line below this represents an additional 50 m distance.

6. Results of measurements with closed boxes

The scale model measurements have also been done in completely closed models, see figure 19. This gives the opportunity to calculate the reverberation time as in 'real life' [39], since the echogram is comparable to a measurement in an existing sports hall, see figure 20. Figure 22 shows the EDT values after correction for air absorption, as derived from the measured Schroeder curves of figure 21. Some EDT values are not shown because they are unreliable.

Three results are striking.

1. As expected, the early decay time (EDT) becomes shorter with increasing frequency.
2. Profile B and C result in shorter reverberation times (T_{5_15} and EDT) than profile A with the only difference being their shape. This matches the previous results of the Schroeder curves.
3. The expected shorter early decay time (EDT) for low frequency sound for profile B, BB and C is found at the 250 Hz frequency band. A look at the Schroeder curves in figure 21 gives more information: the sound pressure level is clearly lower for profiles AA, BB, B and C compared to profile A at all frequencies.



Figure 19 – Measurement setup of the 'closed box'.

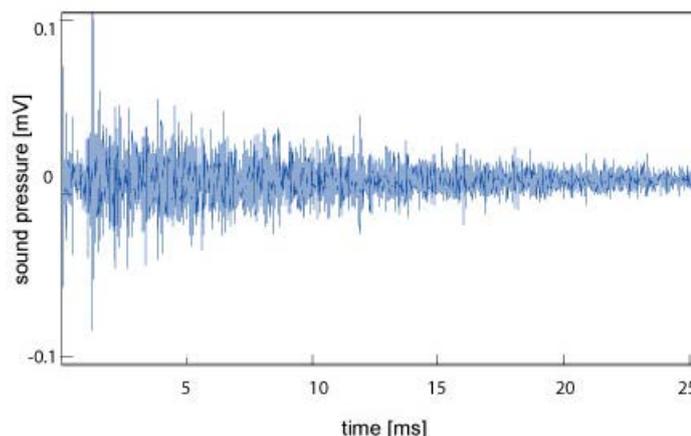


Figure 20 – Impulse response diagram of a measurement in the 'closed box'.

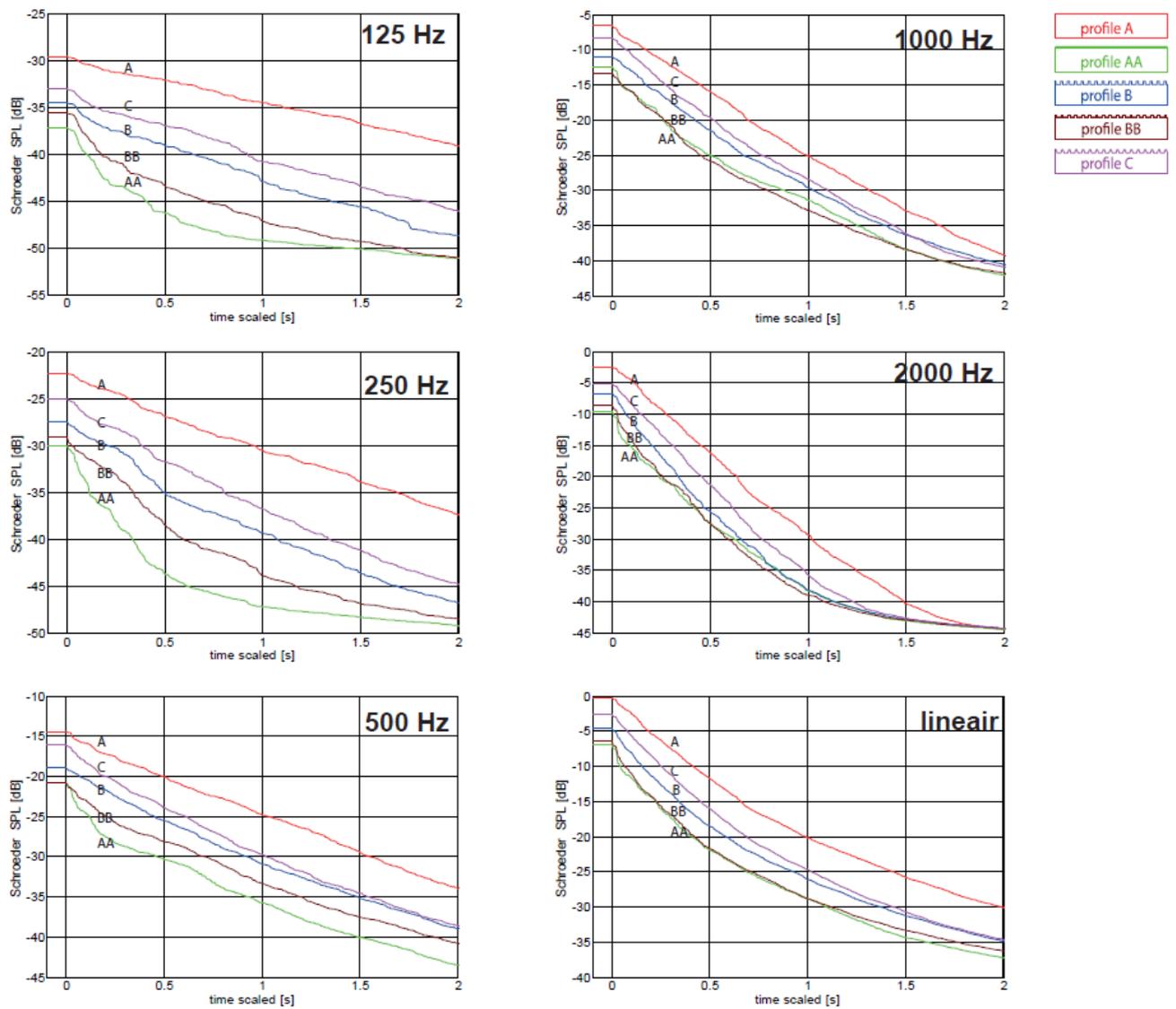


Figure 21 – Schroeeder curves of ‘closed box’ measurements on profiled roof structures with (AA, BB) and without absorption (A, B, C). Results per octave frequency band.

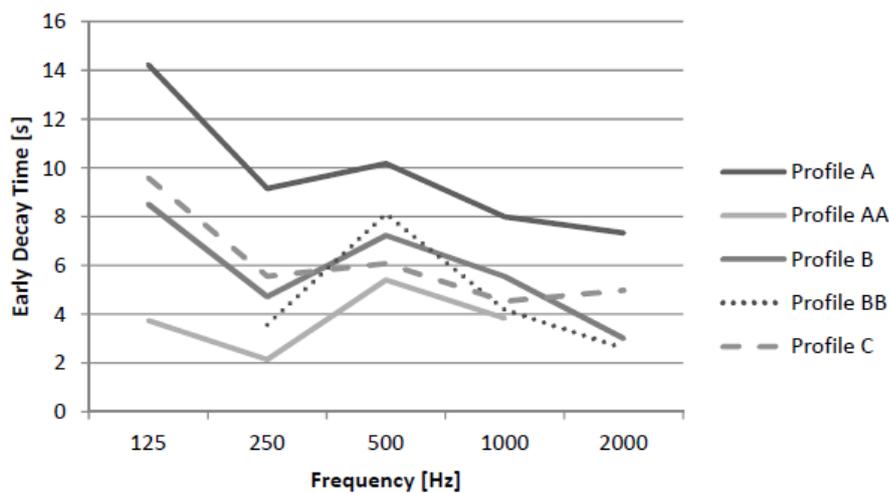


Figure 22 – Reverberation times of ‘closed box’ measurements.

7. Discussion

According to the measurement results, the amount of low frequency sound in a sports hall can be reduced by the shape of a roof structure. The slits in the tested profiles cause strong scattering, some friction and phase shifting effects. Therefore, the sound pressure of the reflection decreases. This 'absorption without any sound absorbing material' is comparable to adding a layer of sound absorbing material and could be a useful way to improve the acoustics in a sports hall. As discussed during the previous section, this effect is strongest at low frequencies of 125 and 250 Hz and to a small extent 500 Hz.

Sports halls constructed with perforated steel panels seem to behave differently than sports halls constructed with stone-like materials. This can be observed from the measured reverberation time (RT or EDT) but can be found even more clearly by inspecting the echograms and Schroeder curves. Although the RT and/or EDT is what people experience, the Schroeder curves provide important diagnostics information relevant for acoustics consultants. When trying to improve the acoustics of a 'bad' sports hall, the information of Schroeder curves should therefore be taken into account.

Furthermore, this study has shown that a scale model is a good tool to investigate the effects of different roof structures on the sound field in a sports hall. Although, a note has to be made. The spark pulse used for this research could not easily produce low frequency sound. This was a disadvantage because of this research's special interest in this type of sound. A larger power spark source could be used which is better able to produce low frequency sound. Most other sound sources, however, are too large for scale model research. The spark pulse, therefore, is still among the best options for this type of research.

8. Conclusion

The main questions to be answered by the scale model measurements were: 'Does the sound absorbing behaviour of a roof structure depend on its shape?' and 'Can the high absorption coefficient of a profiled perforated panel roof structure at low frequencies be explained by its shape?' The first question can be answered with 'yes'. The second question is more complicated.

The measurements and the simulations showed that the high sound absorption values of a perforated panel roof structure at 125 and 250 Hz can be (partly) explained by its shape. The diffusing properties of the corrugated roof have an effect similar to sound absorption. Because the roof is the largest absorbing surface in a sports hall, this effect can have a significant effect on the low-frequency reverberation time.

9. References

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