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SOUND DECAY AND STEADY-STATE LEVEL IN ROOMS WITH CEILING TREATMENT

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ABSTRACT
The aim of this paper is to describe the behaviour of sound field in rooms with absorbent ceiling treatment in respect to steady-state sound pressure levels (SPL) and sound decays. It is shown that the reverberation time and steady-state SPL's are determined by different parts of the sound field and that they are weakly related to each other. As an example, two rooms with equal reverberation times can have significantly different influence on the steady-state SPL's. This is in contradiction to the diffuse field theory. Measurement results from eight classrooms with different ceiling treatments are presented. Formulas for estimating the reverberation time and the decrease in SPL in rooms with ceiling treatment will be presented as well.

INTRODUCTION
In many public rooms such as classrooms, day-care centres, offices etc. the acoustical treatment consist of a suspended absorbent ceiling. In these rooms, the conditions and relations for the diffuse field theory are not fulfilled. Reverberation time as calculated by Sabine formula often show large discrepancies to measured values. It is also recognized that even if the reverberation times are equal, the acoustical conditions can still be perceived as different. Consequently, there is a need for supplementary acoustical descriptors for a more complete description of the acoustical conditions in this type of rooms. From concert hall acoustics it's known that up to five or six parameters are needed to represent the subjective impression of a sound field [1]. Thus, it seems plausible that the reverberation time, even in ordinary rooms, needs some assistance for a more relevant characterisation of the acoustical conditions. In this paper, we will focus on the behaviour of the decay process and the steady-state SPL in rooms with absorbent ceiling treatment. At first, some measurement results from eight classrooms with different ceiling treatments will be discussed. The results show that the reverberation time (T_{20}) and the steady-state SPL are weakly connected and has to be evaluated separately i.e. it is not possible outgoing from reverberation time measurements to foresee the influence on the steady-state noise levels. This is contradictory to the diffuse field assumptions. Secondly, a theoretical model is outlined that describe the behaviour of the sound fields in rooms with ceiling treatment and explain the measurement results. Because of the model, some simple formulas for estimating reverberation times and steady-state sound pressure levels are presented.

MEASUREMENTS
Reverberation time and sound pressure level (SPL) were measured in eight classrooms. An omni directional loudspeaker with constant sound power level was used for the SPL measurements. The measurement procedure follows the guidelines in ISO 3382:1. In each classroom two types of absorbent ceiling treatment was tested. The practical absorption coefficients [4] for the ceiling absorbers are shown in figure 1. The two types of absorbers were grouped as case 1 and case 2. It was not exactly the same type of absorbers within each case but the variation in the absorption coefficients were small, as indicated in figure 1.

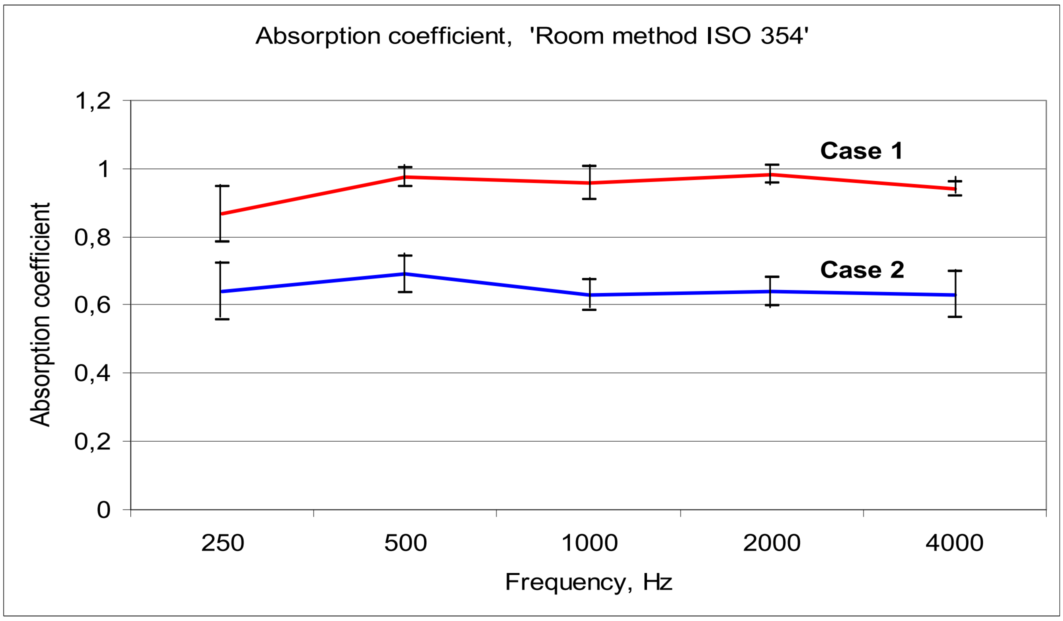

Figure 1. Absorption coefficients for the two types of ceiling treatment

In figure 2, the measured differences in reverberation time between the two cases are compared with the calculated ones according to Sabine formula. It follows that the differences are much smaller than expected. In figure 3 the differences in SPL decrease between the two cases are calculated using measured reverberation times and the assumption of a diffuse sound field i.e. the SPL difference is given by 10log(T2/T1). These differences are compared with measured ones. Thus, despite the fact that there are small differences in reverberation times, indicating small differences in SPL, there are significant differences in SPL decrease between the two cases.

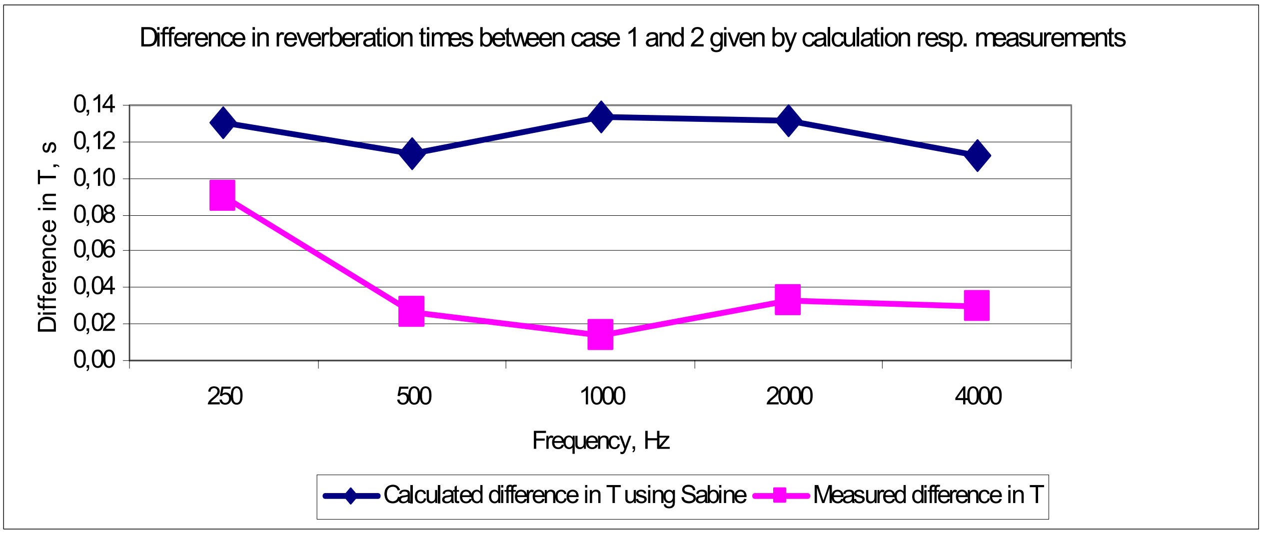

Figure 2. Calculated (Sabine) and measured rev. time

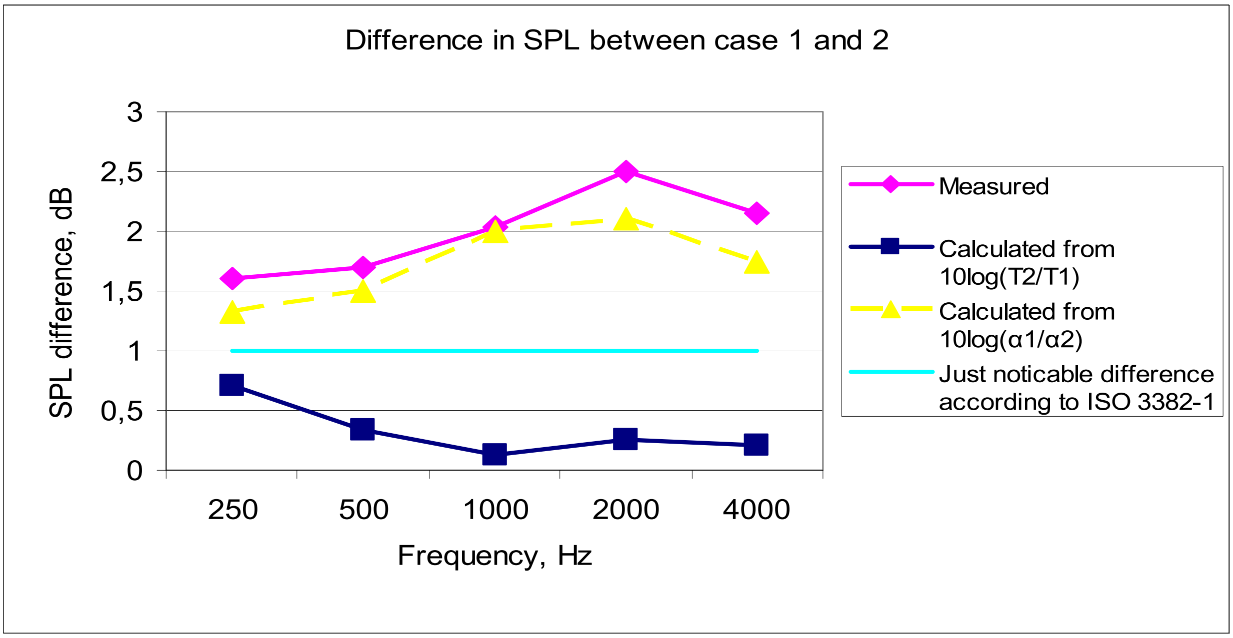

Figure 3. Differences in SPL, calculated and measured

The dashed curve in figure 3 is the SPL difference calculated with the practical absorption coefficient as given in figure 1. Using the practical absorption coefficients and the diffuse field assumption the correspondence between measured and calculated values increase. The limit corresponding to just noticeable difference according to ISO 3382-1 is also given in figure 3. The results in figure 2 and 3 indicate that there is a weak connection between the measured reverberation time and the practical absorption coefficient. However, between the SPL and the practical absorption coefficient the connection is stronger.

THEORY

In rooms where the main absorption is concentrated to one of the surfaces e.g. the ceiling, a subdivision of the sound field into a grazing and non-grazing group is suitable [2] [3]. The term grazing and non-grazing refer to the propagation direction of the sound waves relative the ceiling absorber. The non-grazing group comprises waves with oblique incidence towards the ceiling absorber. A method for subdividing the sound field into a grazing and non-grazing part is given in [2].

The subdivision of the sound field into two groups results in a simple interpretation of the effect of scattering objects. It is assumed that the main effect of sound diffusing objects in rooms with ceiling treatment is to divert energy from the grazing to the non-grazing group. Using the concept of SEA (Statistical Energy Analysis) the effect of scattering objects can be quantified in the coupling loss factor from the grazing to the non-grazing group. Thus, the subdivision of the sound field results in two coupled systems where the coupling mainly is due to the scattering objects such as furnishing and other equipment. The behaviour concerning decay processes and sound pressure levels are analogous to the situation for two coupled rooms.

Applying the formalism of SEA, the decay of the energy level in a room with absorbent ceiling is given by

$$L_E(t) = 10\log(E_{ng}(\Delta N_{ng})e^{-2\pi f\eta' t} + E_g(\Delta N_g)e^{-2\pi f\eta'' t}) \quad (1)$$

$L_E(t)$ is the energy level at time t. E_{ng} and E_g is the energy in the non-grazing and grazing sound field. The decay of the energy in the two system is controlled by η' and η'', respectively. ΔN_{ng} and ΔN_g are the number of modes in each system, respectively. Finally, f is the frequency.

In rooms with ceiling treatment and a small amount of diffusing objects, the decay curve is normally determined by the last term in equation 1, i.e. the grazing field. The decay of the grazing field is preferably given by the grazing absorbing properties of the ceiling absorber, the wall absorption and the amount of sound scattering objects in the room. This implies that the reverberation time is not given by Sabine formula and that non-absorbent objects in the room will influence the decay.

The first term in equation 1 will normally determines the sound pressure level in the room for continuous sound sources. This is because at high frequencies the number of waves (modes) related to the non-grazing (oblique) field is much higher than the number of grazing waves. Thus, the energy level in the room is given by non-grazing waves. This justifies the assumption of diffuse field conditions and the use of the statistical (practical) absorption coefficients. Consequently, we have a situation were the sound pressure level and the reverberation time not are related by the diffuse field assumption and the commonly used power-balance equations. Two a certain extents they act independently and have to be evaluated separately. This means e.g. that two ceiling absorbers that gives the same reverberation time in a room not necessarily has the same influence on the steady-state sound pressure level from a continuous sound source.

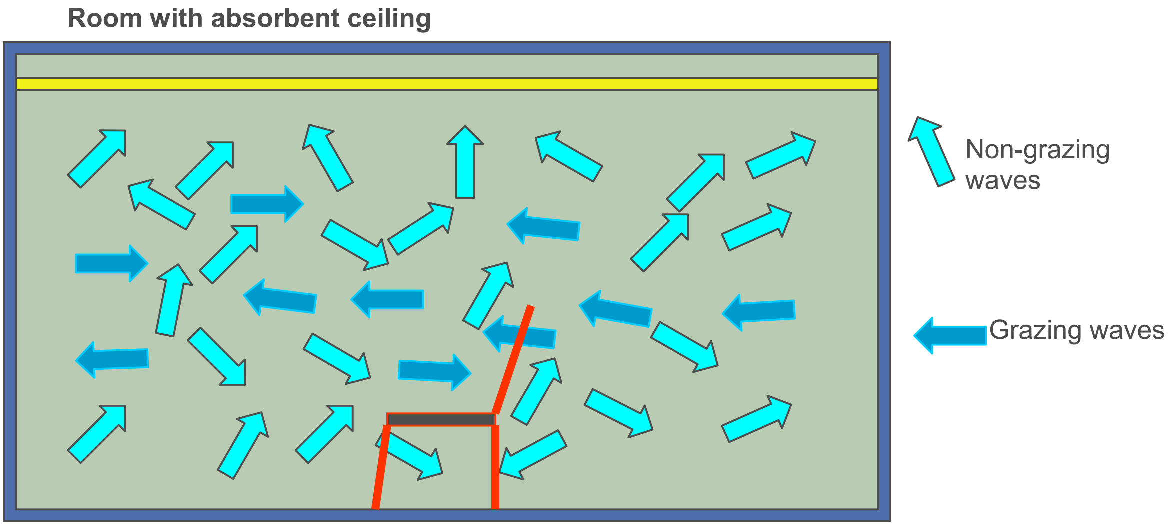

Figure 4. Steady-state situation. Diffuse sound field. Small influence of non-absorbing scattering objects.

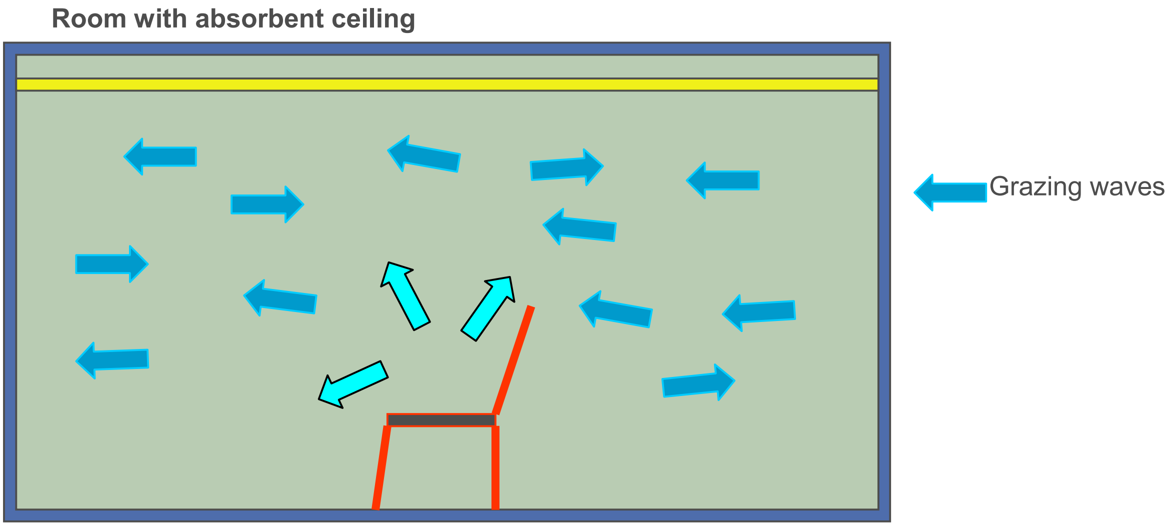

Figure 5. Decay situation. Non-diffuse (grazing) sound field. Large influence of non-absorbing scattering objects.

A reverberation formula for rooms with ceiling treatment
Assuming that the reverberation time in rooms with ceiling treatment is determined by the grazing component of equation 1, i.e. the second term, a formula for the reverberation time is given by

$$T = 0.128\frac{V}{A} \qquad (2)$$

T is the reverberation time, V the room volume and A is the equivalent absorption area. The grazing sound field can be described as an almost two-dimensional field since the main contributions are from waves travelling in a plane parallel to the ceiling absorber. Thus, equation 2 can be considered as the two-dimensional equivalent to Sabine formula.

However, a most important distinction is the interpretation of the equivalent absorption area. The equivalent absorption area in equation 2 also contains the effect of scattering objects in the room. It is assumed that the dominating effect of scattering objects is to divert sound energy from the grazing to the non-grazing field. Thus, for the grazing field this flow of energy to non-grazing field appears as absorption of sound and can be quantified in an equivalent scattering absorption area denoted A_{sc}. The energy flow from the non-grazing to the grazing field is ignored which, at least for the high frequencies, seems to be a reasonable approximation.

Another difference is the way the ceiling absorber is taken into account. The statistical absorption coefficient do not enters equation 2, instead the ceiling absorbers properties for almost grazing incidence appear as a grazing absorption coefficient. This absorption area is denoted $A_{g,ceiling}$. Even the grazing absorption for the floor is included in $A_{g,ceiling}$, however this contribution is assumed small.

Both A_{sc} and $A_{g,ceiling}$ can be estimated using equation 2 and from measurement in a reverberant room. $A_{g,ceiling}$ is measured in a reverberant room without scattering objects. Measurements with and without ceiling absorbers are performed. Using equation 2 the $A_{g,ceiling}$ is given by

$$A_{g,ceiling} = 0.128V\left(\frac{1}{T_{with}} - \frac{1}{T_{without}}\right) \tag{3}$$

A_{sc} is measured in a reverberant room with a highly absorbent ceiling. Measurements with and without scattering objects are performed, and analogously to the calculation of $A_{g,ceiling}$, the A_{sc} is given by equation 3. The total equivalent absorption area in equation 2 is

$$A = A_{g,ceiling} + A_{sc} + A_{walls} + A_{air} \tag{4}$$

A_{walls} is the equivalent absorption area for the walls and is sufficiently estimated by the statistical absorption coefficient for the wall material. A_{air} is the damping in air given by πmV where m is the power attenuation coefficient in air.

Steady-state sound pressure level difference

For the steady-state situation, the sound field can be assumed as sufficiently diffuse and the statistical absorption coefficients will quite accurately describe the absorption process. Since the sound field is diffuse the influence of non-absorbing scattering objects on the steady-state sound pressure level will be small.

Assuming that the ceiling absorber dominates the absorption in the room, the SPL difference between case 1 and 2 is approximately given by

$$\Delta L = 10\log(\alpha 1 / \alpha 2) \tag{5}$$

where α1 and α2 are the practical absorption coefficients for case 1 and 2 respectively.

CONCLUSIONS

In rooms with absorbent ceiling treatment there is a need for supplementary descriptors besides the reverberation time for a relevant characterisation of the acoustical conditions. It is shown that the steady-state sound pressure levels and the reverberation times are not related according to the classical diffuse field theory and hence has to be evaluated separately since they depends on different components of the sound field. The reverberation time is mainly determined by sound waves propagating almost parallel to the ceiling and is to a large extent affected by non-absorbing objects in the room. In that respect the reverberation time is a configuration parameter not only related to the sound absorption but also to the amount of sound scattering objects and the location of the absorbers. The steady-state sound pressure level is related to the diffuse part of the sound field, mainly determined by the total amount of sound absorption in the room, and much less influenced by sound scattering objects.

References

1. M. Barron. The development of concert hall design – a 111 year experience. Spring Conference 2006, University of Southampton, Rayleigh Medal Lecture.
2. E. Nilsson. Decay processes in rooms with non-diffuse sound fields. Part 1: Ceiling treatment with absorbing material. J. of Building Acoustics 11 no.1 (2004) 39-60.
3. E. Nilsson. Decay processes in rooms with non-diffuse sound fields. Part 2: Effect of irregularities. J. of Building Acoustics 11 no.2 (2004) 133-143.
4. ISO 11654 Acoustics – Sound absorbers for use in buildings – Rating of sound absorption