



SOUND SCATTERING IN ROOMS WITH CEILING TREATMENT

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ABSTRACT

The objective of this paper is to present a simple model for calculating the reverberation time in rooms with ceiling treatment. The model assumes that the sound field in rooms with absorbent suspended ceilings could be divided into a grazing and a non-grazing part. Further, that the reverberation times are determined by the grazing component of the sound field. Furniture's and other equipment in rooms with ceiling treatment will have a large influence on room acoustical parameters. In order to take this effect into account a measure denoted equivalent scattering absorption area is introduced. The measure quantifies the scattering effect of objects in rooms and is suited for the reverberation time formula presented. The measure is analogue to the equivalent absorption area used in Sabine formula. An example of a reverberation time calculation for a typical classroom is presented as well as measured data on the equivalent scattering absorption area for classroom configurations.

1 INTRODUCTION

In many rooms such as classrooms, day-care centres, offices, dining rooms, gymnasiums etc. the acoustical treatment consist of an absorbent suspended ceiling. In these rooms the conditions for the diffuse field theory and the well-known Sabine's formula are not fulfilled. The presence of furniture and equipment in rooms with ceiling treatment will influence acoustical parameters such as reverberation time, sound pressure levels, STI-values among others. Thus, there is a need for a method and a parameter to measure and quantify the effect of sound scattering objects in rooms with ceiling treatment. In spite of the fact that rooms with ceiling treatments are more common in public buildings than 'Sabine' rooms the acoustical behaviour of the former ones are less investigated. For that reason it is also the intention of this paper to present a model that elucidates some of the acoustical properties of rooms with ceiling treatment. From this model a reverberation time formula is extracted. The formula incorporates a measure that quantifies the scattering effect of objects such as furniture's and other equipment. The measure is denoted equivalent scattering absorption area due to its resemblance with the equivalent absorption area as used in Sabine's formula.

2 THEORY

2.1 Reverberation time and sound pressure level

A short review of a theoretical model that handles some of the properties in rooms with ceiling treatment is presented. A more profound description is given in [1], [2].

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 [1]. 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 [1].

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

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

$L_E(t)$ is the energy level at time t . E_{ng} and E_g are 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. 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 also 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 due to the fact that 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 absorption coefficient to estimate the effect on the sound pressure level in the room.

Consequently, we have a situation where the sound pressure level and the reverberation time are not related by the diffuse field assumption and the commonly used power-balance equations. To a certain extent they act independently and have to be evaluated separately. This means e.g. that two ceiling absorbers that give the same reverberation time in a room do not necessarily have the same influence on the steady-state sound pressure level from a continuous source. This is illustrated in figure 1. The left diagram shows the reverberation times in a typical classroom and for two types of ceiling treatments. The ceiling treatments correspond to class A and C absorbers according to ISO 11654 [3]. At high frequencies there is a small difference between the efficiency of ceiling absorbers. At low frequencies the class A absorber gives shorter reverberation times. The reverberation times given by Sabine formula for the two ceiling treatments are also presented in the figure. It's clear that the calculation using statistical absorption coefficients and Sabine formula do not agree with measured reverberation times.

The figure to the right shows the difference in the decrease of the sound pressure level in the room for the two cases of ceiling treatment. A loudspeaker working as a constant sound power source generates the sound pressure. Comparing the two figures shows that the ceiling corresponding to the class A absorber decreases the sound pressure level by 1.5 to 3 dB more than the case corresponding to the class C absorber. Thus, even if there are small differences in reverberation times there are significant differences in sound pressure levels.

2.2 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

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

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} [4]. 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. Using equation 2 it is not the statistical absorption coefficient that enters the equation, instead it is the ceiling absorbers properties for almost grazing incidence that 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

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

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

$$A = A_{g,ceiling} + A_{sc} + A_{walls} + A_{air} \quad (4)$$

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.

2.3 Estimation of equivalent absorption areas

The grazing absorption for a class A and class C ceiling absorber was measured in a reverberant room. No significant scattering objects were present in the room and $A_{g,ceiling}$ was calculated according to equation 3. By dividing $A_{g,ceiling}$ with the ceiling area a corresponding grazing absorption coefficient is obtained.

For a typical classroom configuration consisting of tables and chairs the A_{sc} was measured. The measurements were performed in a reverberant room with a class A ceiling treatment and carried out with and without furniture's in the room. A_{sc} was then calculated using equation 3.

By dividing A_{sc} by the number of objects A_{sc}/object is given. Objects in this case consist of a table and two chairs.

In a normal classroom with an absorbent ceiling one part of the energy that hits the walls will be scattered and the other part will mainly loss energy due to dissipation. To estimate the amount of energy scattered and dissipated a series of measurements were performed in nine classrooms. From these measurements and by using equation 3, it was possible to determine $A_{\text{wall,diss}}$ and $A_{\text{wall, sc}}$. Dividing $A_{\text{wall,diss}}$ and $A_{\text{wall, sc}}$ by the wall area yields the corresponding absorption coefficients.

The determined absorption coefficients and equivalent scattering absorption area are summarised in table 1.

Table 1. Absorption coefficients and equivalent scattering absorption area.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
$\alpha_{\text{wall,sc}}$	0.19	0.17	0.13	0.12	0.13	0.12
$\alpha_{\text{wall,diss}}$	0.12	0.12	0.12	0.13	0.13	0.15
$\alpha_{\text{g,ceiling,class A}}$	0.08	0.16	0.08	0.08	0.07	0.07
$\alpha_{\text{g,ceiling,class C}}$	0	0.01	0.07	0.10	0.08	0.08
$A_{\text{sc,furniture/object}}$	0.01	0.47	0.57	0.40	0.36	0.42

It's to be observed that $\alpha_{\text{g,ceiling}}$ corresponds to small values and that the absorption coefficients related to scattering and dissipation are of the same size.

2.4 An example

Using equation 2 and the values in table 1 the reverberation times has been calculated for the classroom corresponding to the measured results in figure 1, left and right. In the classroom 27 objects, containing a table and a chair, were present. Thus, multiplying the $A_{\text{sc,furniture/object}}$ in table 1 with 27 gives the equivalent scattering absorption area due to the tables and chairs. The calculated reverberation times are shown as dashed curves in figure 1. The agreement is satisfactory except at 125 Hz for the class A absorber. This difference is due to the extra low frequency absorption that was supplied to the classroom but which was not included in the measurement of $\alpha_{\text{g,ceiling,class A}}$ in table 1. The reverberation times given by Sabine's formula are also presented in figure 1.

In figure 1 right, the difference in capacity of decreasing the noise from a steady-state noise source is shown. Despite the fact that the reverberation times at high frequencies are almost equal, there are significant differences in the ability of decreasing the noise. For comparison, calculated sound pressure level differences are shown. The calculation is based on diffuse field theory using statistical absorption coefficients.

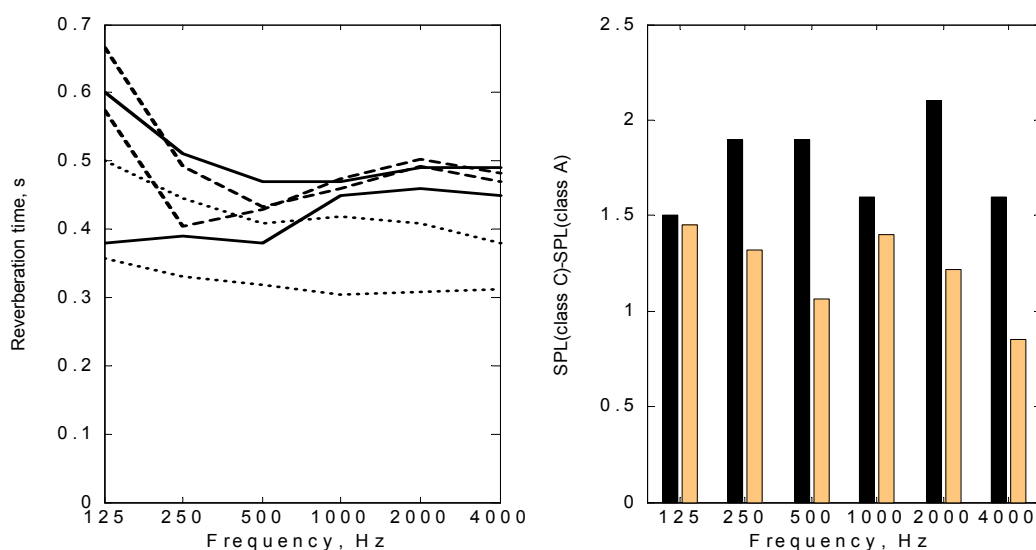


Figure 1. Left figure, from above at 125 Hz: calculated class C, measured class C, calculated class A, Sabine class C, measured class A, Sabine class A. Right figure, dark bars, measured SPL difference, light bars, calculated SPL difference using diffuse field theory.

3 CONCLUDING REMARKS

In rooms with absorbent ceiling treatment sound scattering objects such as furniture's will have a significant influence on reverberation time. A reverberation time formula suitable for rooms with ceiling treatment is presented. A measure denoted equivalent scattering absorption area is introduced to quantify the scattering effect of objects. It is emphasised that the simple relation between reverberation time and sound pressure level as given by the diffuse field theory normally not is valid in rooms with absorbent ceilings. Generally these parameters have to be evaluated separately.

REFERENCES

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