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How much scattering is sufficient to soften the Hard Case?

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Summary
A common case in room acoustics is a cuboid room with acoustically hard walls and soft ceiling, previously labeled by this author as The Hard Case. Examples of common Hard Cases are classrooms, sport halls, canteens, corridors and rooms for meetings and conferences. Due to the fact that its acoustics have proved to be hard to predict, The Hard Case label has double meaning. As long as the hard surfaces have sufficient degree of scattering, the reverberant sound field of the Hard Case will basically be diffuse and thus its reverberation time can be predicted with Sabine's Formula. On the other hand, if the walls are more or less plane, parallel surfaces, the acoustics of The Hard Case will behave differently in different frequency ranges. At low frequencies, reverberation times close to Sabine RT are commonly found, even if conditions are non-diffuse and dominated by separate modes. Above some not yet defined critical frequency, long RTs and flutter-echoes are observed, only limited by wall scattering and air absorption.
This paper presents and discusses the results from a scale model experiment and a full scale experiment where the Hard Case and the effect of geometrical modifications to its vertical boundaries were investigated. Both experiments bring evidence of a horizontal reverberant field in the Hard Case. Moreover, their results support the hypothesis about the ceiling absorber having a strongly frequency dependent effect on gracing modes. Both experiments have a specific practical implication: Hard diffusers on the walls can, in the proper amount, provide a diffuse sound field with reverberation times that will converge at the RT predicted by Sabine's Formula, even if all the absorbers of the room is concentrated in the ceiling. Further, the apparent change in absorption area when the first diffusers are introduced is equal to the wall area the added diffusers occupy. The mechanism appears to be that wall diffusers in the Hard Case redirect reverberant energy, from the horizontal field, into the ceiling absorber. Given a Hard Case with the absorption area A concentrated in the ceiling, it is concluded from the results that if diffusers are distributed to cover a wall area equal to A/3 on each of two walls in L-configuration, or A/6 on each of the four walls, it would be sufficient to soften the Hard Case, i.e. to achieve $T=0.16\cdot V/A$. For this purpose, diffusers capable of redirecting energy from horizontal plane to vertical directions should be chosen.
In further work, the angle- and frequency dependency of the mineral wool absorber will be investigated, especially the frequency dependent absorption effect in mineral wool on gracing modes and gracing wave incidence.

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1. Introduction

A common case in room acoustics is a cuboid room with acoustically hard walls and soft ceiling, previously labeled by this author as The Hard Case. Examples of common Hard Cases are classrooms, sport halls, cantinas, corridors and rooms for meetings and conferences. Due to the fact that its acoustics have proved to be hard to predict, The Hard Case label has a double meaning. As long as the hard surfaces have sufficient degree of scattering, the reverberant sound field of the Hard Case will basically be diffuse and thus its reverberation time can be predicted with Sabine's Formula. On the other hand, if the walls are more or less plane, parallel surfaces, the acoustics of The Hard Case will behave differently in different frequency ranges. To “soften the Hard Case” would equivalent to making the sound field more diffuse.

At low frequencies, reverberation times close to Sabine RT are commonly found, even if conditions are non-diffuse and dominated by separate modes. Above some not yet defined critical frequency, long RTs and flutter-echoes are observed, only limited by wall scattering and air absorption. In a scale model experiment, RTs up to seven times longer than those predicted by Sabine's Formula was found in the high frequency region when there were no diffusers on the walls. When diffusers were introduced, one after another, RT's became shorter and eventually approached Sabine values. While this demonstrates a safe way to solve the Hard Case problem, such extra wall elements are often impractical or unwanted for economical or aesthetical reasons. Moreover, in many practical cases such elements are superfluous wherever windows, doors, columns, furniture and other natural diffusers causes RT's close to those predicted by according to Sabine. It remains to solve several theoretical problems in the Hard Case, such as the definition of the aforementioned critical frequency. When it comes to practical consequences, it is absolutely crucial to explore the delicate difference between cases of too little scattering and cases of sufficient scattering, e.g. to find out just how big can plane, parallel wall segments be without causing deviations from RTs predicted by Sabine. In the building industry there is not just a request for “sufficient”, there is a request for “just sufficient”.

2. Previous work

It has been demonstrated theoretically that horizontal reverberant sound fields (HRSFs[1]) may occur in rooms with reflective boundaries except for a sound absorbing ceiling, and that the reverberation times in such rooms would depend strongly on scattering abilities of the vertical boundaries [1]. Basically due to gravity, common practice leans toward exact vertical orientation of vertical boundaries. Thus, the orientation of the boundaries inherently supports HRSFs. However, if the plane, vertical surfaces of doors, windows, frames, profiles, or other elements in a wall, deviate from a single plane, this deviation would counteract specular reflections. As a consequence, energy would be dissipated from the horizontal field and eventually be absorbed by the ceiling. Indeed, elements creating such deviations act like diffusers. From theory, it is expected that the depth D of steps or recesses in a surface would imply a lower frequency limit, $kD=1$, for the scattering effect, k being the wave number. Above this critical frequency it was predicted that such natural diffusers would make the ceiling absorber more effective.

3. Recent work

1.1. Scale model measurements in a Hard Case

In a student research project [2], it was demonstrated by experiments in a 1:4 scale model of a typical 60m^2 Hard Case classroom, (3.0m*6m*10m), that a HRSF existed. The basic properties of the scale model was, see Figure 1,

- Cuboid with hard boundaries except for a sound absorbing ceiling
- dimensions 0.75m*1.5m*2.4m
- Ceiling was 50mm mineral wool below 50mm air space and plywood top
- Plane plywood walls and floor

The random incidence absorption factors of the plywood was measured before introducing the absorber in the ceiling, and then reduced to a minimum by adding proper stiffness to the walls by mounting profiles on the outside.

[1] HRSF, i.e. a sound field dominated by energy of room modes, or rays, without vertical components, i.e. tangential modes in the horizontal plane; With an effective absorbent in the ceiling, all vertical components would have a high decay rate, leaving a reverberant tail dominated by horizontal components.

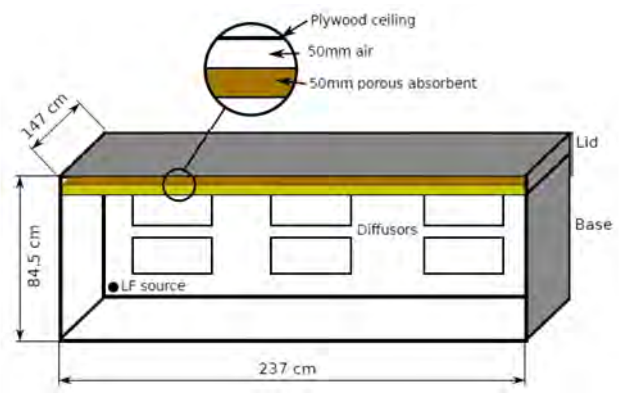

Figure 1. Hard Case scale model

1.2. Frequency dependency in ceiling absorber

When introducing the sound absorbing ceiling in the scale model, its effect on the reverberation times was strongly frequency dependent, see Figure 2 and Figure 3.

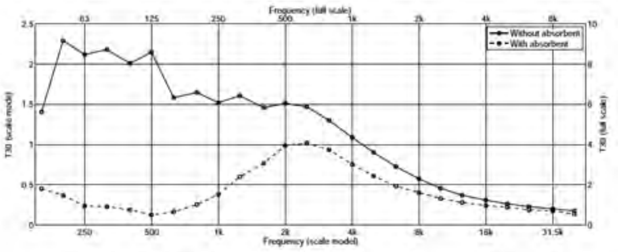

Figure 2. T30 with and without absorber in ceiling

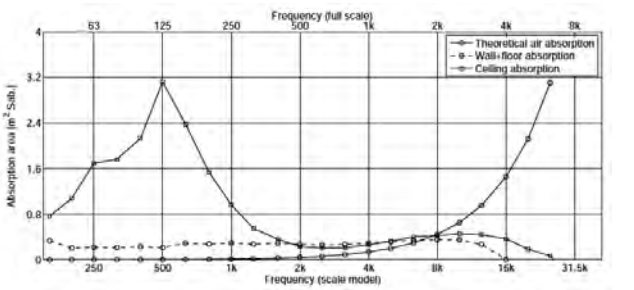

Figure 3. Apparent absorption area (m2Sa) of ceiling absorber, in Hard Case, total absorber area 3.48m^2

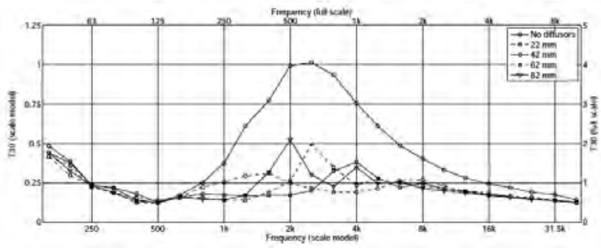

Figure 4. T30 in Hard Case (scale model) with no diffusers, and with hard rectangular elements on walls

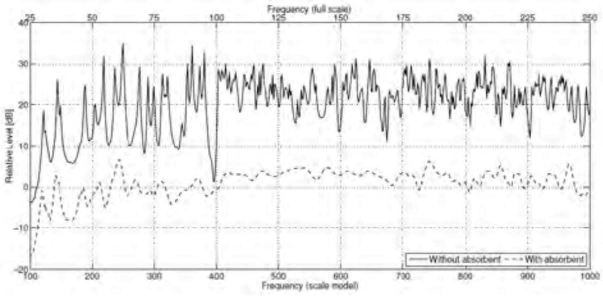

Figure 5. Frequency response with ceiling absorber (dashed curve), and without ceiling absorber (solid curve, shifted upwards for readability). 18 separate modes can be seen below 400Hz (as measured in scale model).

Between 125 and 500Hz, Figure 3, the apparent absorption area from the ceiling absorber is close to what can be predicted from random incidence absorption, for the given material and build-up. Apparent absorption factor peaks at 0.9 at 500Hz, as can be calculated from 3.1m^{2}Sa in the diagram, divided by a total absorber area of 3.4m^2. Above this frequency, the apparent absorption falls drastically off to approximately 0.1 at 2kHz. This corresponds to a reduction to 1/10 over merely two octaves

The drastic fall-off in apparent absorption, from 0.9 at 500Hz to 0.1 at 2kHz, cannot be explained by the random incidence absorption factors of the ceiling absorber, implying that the reverberant sound field is not diffuse. Below 500Hz, where apparent absorption is similar to random incidence measurements, it could seem obvious that the sound field is diffuse or quasi-diffuse. However, this frequency range includes horizontal tangential modes that would become prominent if they were not damped by the ceiling absorber. Such prominent modes are not observed in terms of reverberation times, and the frequency response in Figure 5 indicates that all modes are damped by the presence of the absorber.

A tentative conclusion is suggested:

- Below 500Hz, mineral wool has the ability to absorb gracing modes, despite the fact that such modes have no vector component normal to the absorbing surface
- Above 500Hz, the ability of the ceiling absorber to absorb gracing modes decreases rapidly with increasing frequency

This conclusion is to be tested by more detailed experiments in further work, and theoretical models should be investigated in order to find explanations and be able to predict the sound absorption in mineral with varying frequencies and incidence angles. The computation software Odeon predicts that mineral wool will be reflective for rays at gracing incidence, but not that it will be an effective sound absorber below some frequency limit. Expectedly, explanations are to be found in the wave properties of sound.

1.3. Frequency limits of diffusers due to element thickness

Figure 4 shows the effect of adding hard rectangular elements of 4 different thicknesses to the plain walls. The thinnest element was 22mm thick, and an effect can clearly be seen from 1kHz and upwards. This corresponds to $k\Delta x>0.4$, which is a considerably lower frequency limit than predicted by theory. Note that with thicker elements, more uneven curves are seen, and with 82mm thick elements, there are prominent peaks at 1kHz and 2kHz. At these frequencies, the thickness is equal to a half wavelength and a whole wavelength respectively. The reason for this is most probably due to the density of elements, and their thickness, the space between the elements form resonant wells that are quite narrow compared to their width. Thus they allow standing waves to occur inside of them. As a consequence, there will be pressure maxima in their mouths, in a plane more or less flush with the pressure maxima at the face of the diffuser element, equivalent to a case where the wells and diffuser were replaced with a plane wall. In this frequency region, the diffuser effect “collapse”, and the diffuser-and-wall configuration becomes equivalent to a wall in the plane of the diffuser’s face. Indeed, for the same reason the so-called Schroeder (QRD). diffusers lose their effect above a frequency limit determined by the depth of wells being equal to half a wavelength.

1.4. Apparent absorption effect from rectangular diffuser elements

From the differences in RT observed when introducing hard diffusers on the plain walls, a difference dA’ in apparent absorption area A’ was determined. Remarkably, dA’ happened to have values close to the total area of the faces of the rectangular elements, i.e. the diffusers. In other words, the introduction of hard rectangular elements had the same measurable effect on RT as if they were sound absorbers with absorption factors equal to 1.0. These results can, if verified in further testing, be of great value: It would in most cases be far more practical to have a certain amount (in m^2) of hard elements on walls, than the same amount of absorbers, since the latter often are not robust enough for the intended use of the room.

4. Current work – full scale Hard Case experiment

In order to test the effect of changing the geometrical properties of the vertical surfaces in a Hard Case, an experiment in a full scale room was carried out. Theory [1] would predict that by introducing deviations from the ideal plane of a wall in cuboid room, would introduce modal scattering, thus redirecting more reverberant energy from a horizontal field into the sound absorbing ceiling. For this purpose a canteen with suspended ceiling with mineral wool tiles was chosen. Dimensions and images of the test room are presented in Table 1 and Figure 7.

Table 1. Basic dimensions of the cuboid test room

Height	11,6	m
Width	6,1	m
Length	2,38	m
Volume	168	m^3

All vertical boundaries were acoustically hard, with windows along the façade on one long side, glass wall with 3 doors on the other long side, and end walls consisting of gypsum walls and doors, see Figure 5. Each window was 0.9m wide and 1.66m high, with an area of $1.5m^2$. Hinged at the bottom edge they offered the possibility to be tilted inwards by Δx=14cm measured at the top edge, corresponding to 4.8 degrees deviation from the vertical plane. Assuming the lower frequency limit for modal scattering from such an element, $k\Delta x>1$, we could expect an effect in the frequency region f>387Hz.

Figure 6. Images from the full scale test room. All 9 windows along the façade could be opened, i.e. tilted inwards individually, for a controlled change in the scattering properties of this boundary. In the opposite wall, all doors were closed when the effect of scattering was tested.

Reverberation times were measured with closed doors and analyzed in octave bands, in different window configurations, including

- All boundaries in vertical orientation, all windows closed
- 5 of 9 windows 1.5m^2 each, tilted inwards, total altered surface area dS=7.5m^2
- all 9 windows, tilted inwards, total tilted surface area dS=13.5m^2

Results in terms of T30 are presented in Figure 8.

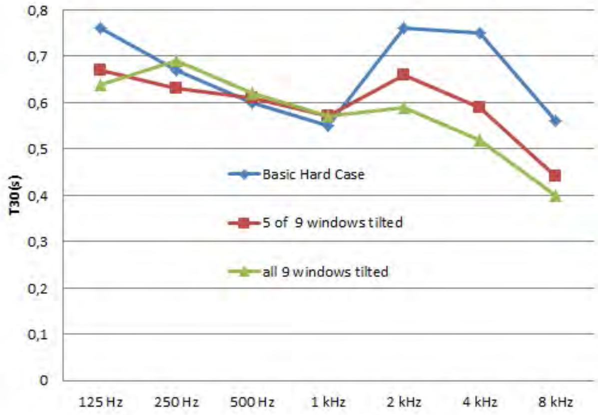

Figure 7. Reverberation times T30 in the test room; "Basic Hard Case" has all windows vertical (closed)

Similar to the scale model case above, the apparent difference in absorption area, dA', corresponding to the tilting of windows, was calculated.

Table 2. Apparent differences in absorption area, dA (m^{2}Sa), corresponding to differences in total area of tilted windows, dS (m^2)

	2kHz	4kHz	8kHz	*dS*
Windows closed (ref.)	0	0	0	*0*
5 of 9 windows tilted	5	10	7	*6.5*
All 9 windows tilted	10	16	13	*13.5*

1.5. Comments to the full scale Hard Case results

From Figure 8 we can see that in its Basic state, i.e. with no tilted windows, the test room exhibits the rise in RT's in higher frequencies that are so often seen in typical Hard Case rooms with mineral wool absorbers in the ceiling. By tilting the windows, this rise in RT is gradually eliminated. The observations can be explained as follows: With no windows tilted the horizontal reverberant field is sustained between parallel vertical surfaces with little surface diffusion. When gradually introducing tilted windows, energy in the horizontal field is redirected to the absorber in the ceiling, i.e. the absorbing potential of the ceiling is being utilized. It is expected that asymptotically, the RT curve would reach the values predicted by Sabine's Formula, as the amount of tilted surfaces increase.

From Table 2 it can be seen that the apparent change in absorption area is on average equal to the total area of tilted windows introduced, thus supporting the explanation that the tilted windows redirect horizontal reverberant energy into the ceiling absorber. This observation is in full agreement with the similar observation in the scale model experiments.

5. How much scattering is sufficient to soften the Hard Case?

An amount and distribution of absorption that would provide for sufficiently diffuse field conditions for the validity of Sabine's Formula, T=0.16·V/A, would be sufficient to soften the Hard Case. In a cuboid with total absorption area A, the sound field could be made sufficiently diffuse for valid predictions of T by distributing the amount of A/3 in all three directions x, y, z. E.g., with A/3 in the ceiling, two walls in L-configuration could have the amount A/3 each, or each of the four walls could have the amount A/6. Now, in the typical Hard Case, the absorption A is all concentrated in the ceiling. From the results of the experiments described in this paper, it can be concluded that if diffusers are distributed so that they cover a wall area equal to A/3 on each of two walls in L-configuration, or A/6 on each of the four walls, it would be sufficient to soften the Hard Case. It remains to settle whether this amount is just sufficient, or one could do with less.

6. Conclusions and Further Work

Both the scale model Hard Case experiment and the full scale Hard Case experiment bring evidence of a horizontal reverberant field in the Hard Case. Moreover, their results support the hypothesis about the ceiling absorber having a strongly frequency dependent effect on gracing modes. Both experiments have a specific practical implication: Hard diffusers on the walls can, in the proper amount, provide a diffuse sound field with reverberation times that will converge at the RT predicted by Sabine's Formula, even if all the absorbers of the room is concentrated in the ceiling. Further, the apparent change in absorption area, dA', when the first diffusers are introduced, is equal to the wall area the added diffusers occupy. The mechanism appears to be that wall diffusers in the Hard Case redirect reverberant energy, from the horizontal field, into the ceiling absorber.

Given a Hard Case with the absorption area A concentrated in the ceiling, it is concluded from the results that if diffusers are distributed so that they cover a wall area equal to A/3 on each of two walls in L-configuration, or A/6 on each of the four walls, it would be sufficient to soften the Hard Case, i.e. to achieve T=0.16·V/A. For this purpose, diffusers capable of redirecting energy from horizontal plane to vertical directions should be chosen.

In further work, the angle- and frequency dependency of the mineral wool absorber will be investigated, especially the frequency dependent absorption effect in mineral wool on gracing modes and gracing wave incidence.

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