ODEON APPLICATION NOTE
Modelling simple rooms in ODEON

AR, GK, CLC, JHR – June 2021

Contents

ODEON APPLICATION NOTE
Modelling simple rooms in ODEON

AR, GK, CLC, JHR – June 2021

Scope

This application note presents the numerical and practical challenges posed by simple geometries in ODEON. The note focuses on one example of a flat rectangular room.

1. Introduction

In room acoustics, simple geometries can prove challenging to study, whether with traditional methods or in ODEON simulations. This might sound paradoxical, but this is exactly because common room acoustic theories assume a certain degree of complexity of the sound field. One of these assumptions is that the sound field is diffuse i.e., isotropic and with waves of random phase.

For ODEON simulations, a well-known limitation is frequency, where results are only reliable above the *Schroeder* limit [1]. You can read more about it in Chapter 9, *Calculation principles*, in the ODEON manual [2]. As an energy model, ODEON does not include phase information in the simulation. Therefore, wave phenomena such as interference and standing waves cannot be represented. Another important condition for reliable simulations is a high reflection density, which is achieved by using a large number of rays. ODEON does not perform as well in anechoic or semi-anechoic environments, where the sound field is composed of only a few early waves (represented by rays), which are quickly absorbed. In particular, diffracted components are modelled only approximately in ODEON, so in the absence of other reflected components, unreliable results can be expected.

This note focuses on the example of a rectangular room, which is commonly seen in buildings. Such rooms are atypical cases, where the sound field may not be diffuse. The reflection between parallel surfaces can trigger flutter echoes, which are usually unwanted. We will see that these rooms are particularly problematic when they present a certain degree of unevenness, for instance in terms of dimensions or absorption properties. The study focuses on reverberation time, which is a widely used room acoustic parameter.

2. Theory

A common way of assessing the room acoustic conditions of a room is to study its reverberation, in other words, how fast the sound energy decays. In that perspective, the reverberation time T_{60} is defined as the amount of time it takes for the sound energy to decrease by 60 dB in the room. A 60 dB decrease from usual sound levels practically means that the sound is not audible any more.

The reverberation time is influenced by the amount of absorption in the room, which has led to well-known predictive formulas. Room acoustic calculations become particularly simple under a set of ideal conditions. In a *three-dimensional diffuse sound field*, with a sufficiently high modal overlap (above the so-called

Schroeder frequency), the acoustic energy is assumed to decay exponentially [3]. This is typically displayed in a dB scale, for which the sound decay with time is a straight line. Under these conditions, the *Sabine equation* relates the absorption in the room to the reverberation time,

$$T = \frac{55.3V}{cA},$$

where V is the volume of the room, c is the speed of sound and A is the absorption area of the room. The Sabine equation can also be expressed as a function of the mean-free path l_m,

$$T = \frac{13.8 l_m}{c\alpha_m},$$

where α_m is the mean absorption coefficient of the room $\alpha_m = \frac{A}{S}$, and S is the total surface area of the room. What makes Sabine's equation so popular, even to this day, is its simplicity and its clear inverse proportionality relation between the amount of absorption in the room and the resulting reverberation time.

The reverberation time can also be evaluated more precisely by measurements or simulations. However, it is challenging to measure a decay of 60 dB, due to the presence of background noise. In that case, the late part of the decay curve flattens (see an example in Figure 1). In simulations, we might also want to avoid calculating 60 dB of decay in order to reduce calculation times.

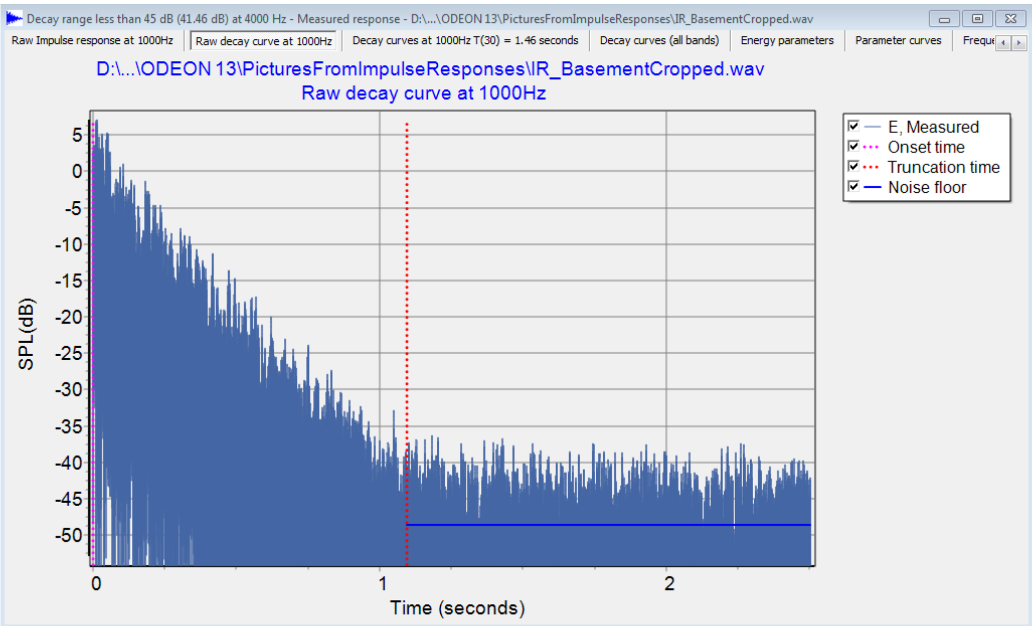

Figure 1: A typical measured impulse response. The curve becomes flat after it reaches the background noise. The 'truncation time' vertical line is located by ODEON automatically and indicates the (left) part of the response not affected by the background noise. From **[2]**.

As a solution, other reverberation time parameters have been developed. The idea is to find the slope of the decay curve on a smaller portion of it, and then to extrapolate it to a 60 dB decay, assuming it is exponential. Some of the parameters used in ODEON are summarised in Table 1.

Table 1: Decay parameters included in ODEON by default.

Parameter	Start	Stop
EDT (Early Decay Time)	0 dB	-10 dB
T_{15}	-5 dB	-20 dB
T_{20}	-5 dB	-25 dB
T_{30}	-5 dB	-35 dB

The EDT (Early Decay Time) focuses on the early part of the decay, containing the direct sound and early reflections. The three other parameters, T_{15}, T_{20} and T_{30}, are estimators of T_{60}, and they focus on the late reverberation, which explains why they measure the decay from -5 dB, in order to exclude the direct sound. It should be noted that EDT varies with position, whereas the other reverberation time parameters characterize the room globally. The parameters are multiplied accordingly so that they are comparable with a 60 dB decay. For instance, for T_{20}, a decay time is first estimated between -5 dB and -25 dB, thus covering 20 dB, so it is then multiplied by 3. In ODEON, the squared impulse response is backwards integrated (this is the so-called *Schroeder curve*) and corrected for truncation, in order to reduce fluctuations [4]. The different reverberation parameters are then found by evaluating the slope of the Schroeder curve, using least-square fitting between the level bounds described in Table 1 [5]. One can totally create other decay parameters, based on different sections of the decay curve.

For a perfectly exponential decay (i.e., straight line in a dB scale), all the decay parameters should yield similar values, provided that they stay above the noise floor. However, if the decay is not exponential, the parameters will differ. Each parameter will then be typical of the level range it was calculated on. For instance, EDT focuses on the early part, whereas T_{30} is more representative of the late part of the decay.

This note focuses on so-called *non-Sabine environments*, in which the decay curves are bended, and therefore the Sabine theory does not hold.

3. A simple example: rectangular room

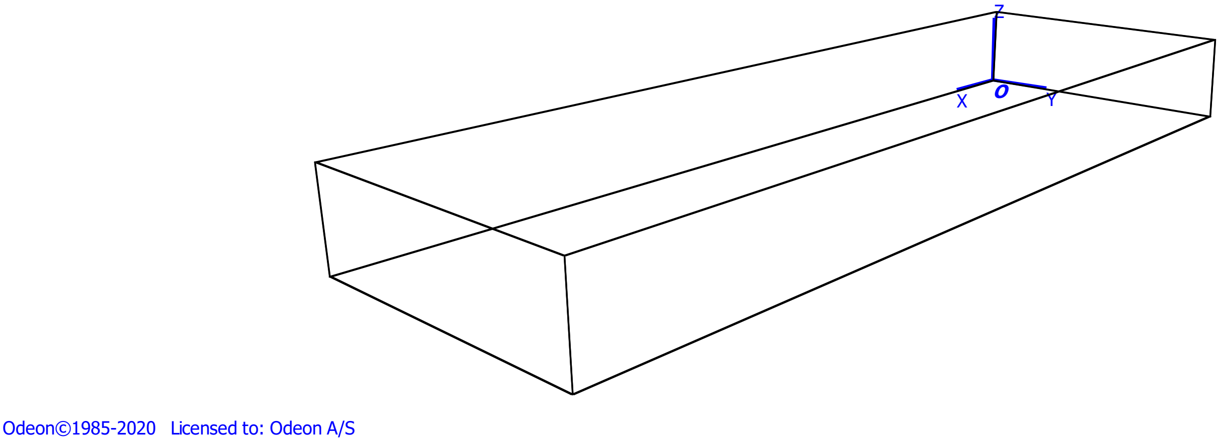

Figure 2: A rectangular room in ODEON with dimensions L*W*H = 30 m * 10 m * 3 m.

Let us consider a rectangular room with dimensions L*W*H = 30 m * 10 m * 3 m (see Figure 2). The dimensions are uneven, and the room is largely flat, with a much smaller height than the two other dimensions. Such uneven geometries are generally not recommended, as they favour strong acoustic phenomena, such as echoes or colouration. Rooms with relatively small aspect ratios behave more regularly. For example, [6] recommends length-to-width ratios between 1.15 and 1.45, although the study focuses on small rooms and modal phenomena (i.e., low frequencies), which cannot be simulated in ODEON.

The surfaces are also assumed smooth, so the scattering coefficient is left to its default value in ODEON (1 %). As a result of the parallelism of the walls and the low scattering, the sound rays in the room do not mix well, which makes the sound field less diffuse, especially in the vicinity of the source. Further away from the source, the sound field becomes more reverberant. This can be well illustrated with the 3D billiard feature of ODEON. Figure 3 is a screenshot of the billiard, where balls are launched from a source in the YZ plane. Most of the balls remain close to this plane due to the low scattering. The same effect occurs in every plane parallel to the boundaries of the room.

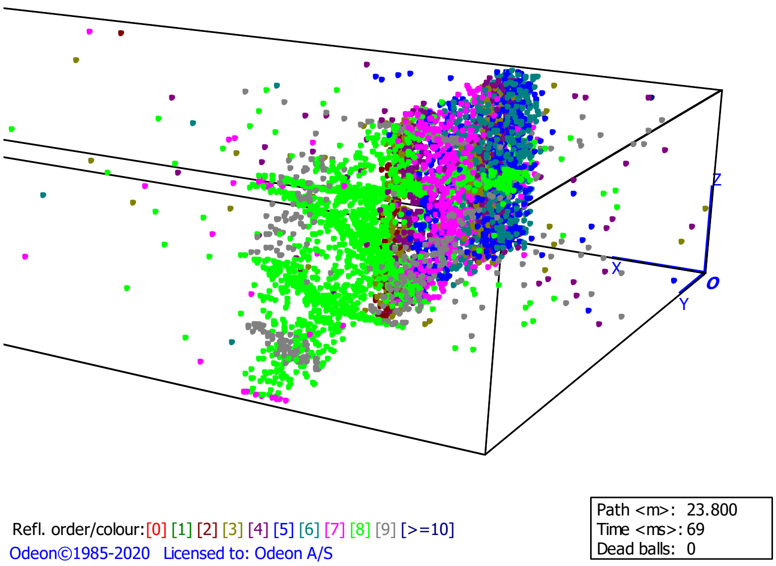

Figure 3: Billiard balls in ODEON, remaining close to the YZ plane due to low scattering at the surfaces belonging to this plane.

In this note, we focus on two conditions:

- **Condition 1:** all surfaces are assigned Material 10 (10 % absorption), so they are rather reflective. We still include a minimum absorption in order to allow the calculation of the Sabine equation.
- **Condition 2:** the ceiling is assigned Material 90 (90 % absorption), which makes it much more absorbing than the other surfaces, still with 10 % absorption.

In Condition 1, the rays propagate over a long distance, despite their deterministic direction, because of the low absorption of the surfaces. After many reflections, the sound field becomes more and more isotropic and closer to a diffuse reverberant field. However, in Condition 2, the small distance between the floor and the ceiling means that the vertical rays are subject to many reflections on the ceiling without being redirected towards other surfaces. Consequently, vertical rays are rapidly attenuated compared to other directions. Hence, the sound field can be understood as two energy systems (see Figure 4):

- A fast-decaying vertical field.
- A slow-decaying horizontal field.

The small amount of scattering in the model means that there is virtually no communication between these two systems. This description is similar to [7], where the sound field is divided into a *grazing field* (modes parallel to the ceiling) and a *non-grazing field* (oblique modes).

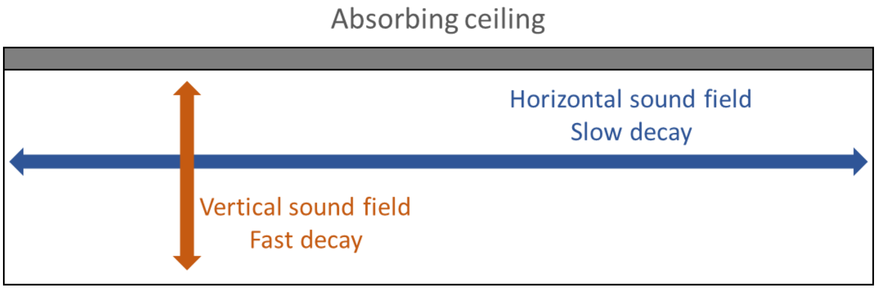

Figure 4: Side-view of the rectangular room, showing the two energy systems that dominate the sound decay.

4. Study of the decay curves

In the following we place one source and two receivers in the room as shown in Figure 5. Receiver 1 is relatively close to the source (4 m), and Receiver 2 is further away (10 m). This section focuses on the Schroeder decay curves calculated at both receiver positions. In classic room acoustic theory, assuming a diffuse sound field, the decay is generally exponential – represented by a straight line in a dB scale.

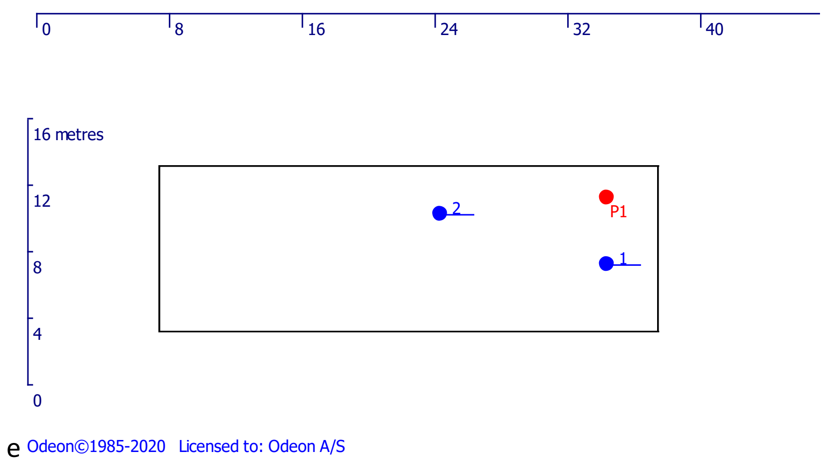

Figure 5: Top-view of the rectangular room with the source and receivers.

Note on the number of rays: especially for Condition 2, where the horizontal field is slowly decaying, we have to use a large number of late rays for the ODEON results to be reliable. We use 10 times the precision setting (that is, 10 x 16000 rays) [2].

4.1. Condition 1: Uniform absorption

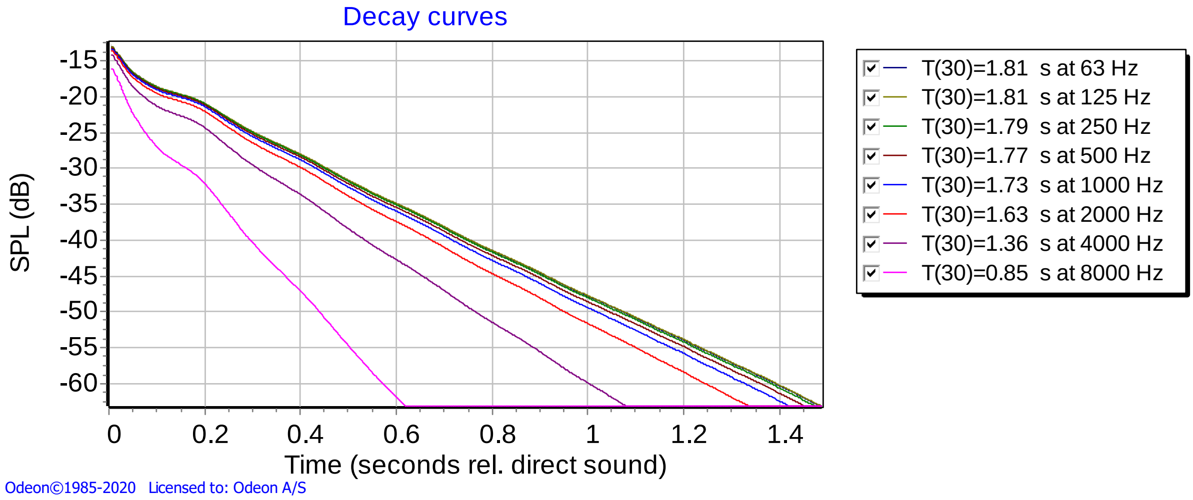

Figure 6: Decay curves for Condition 1 (Reflective surfaces) at Receiver 1.

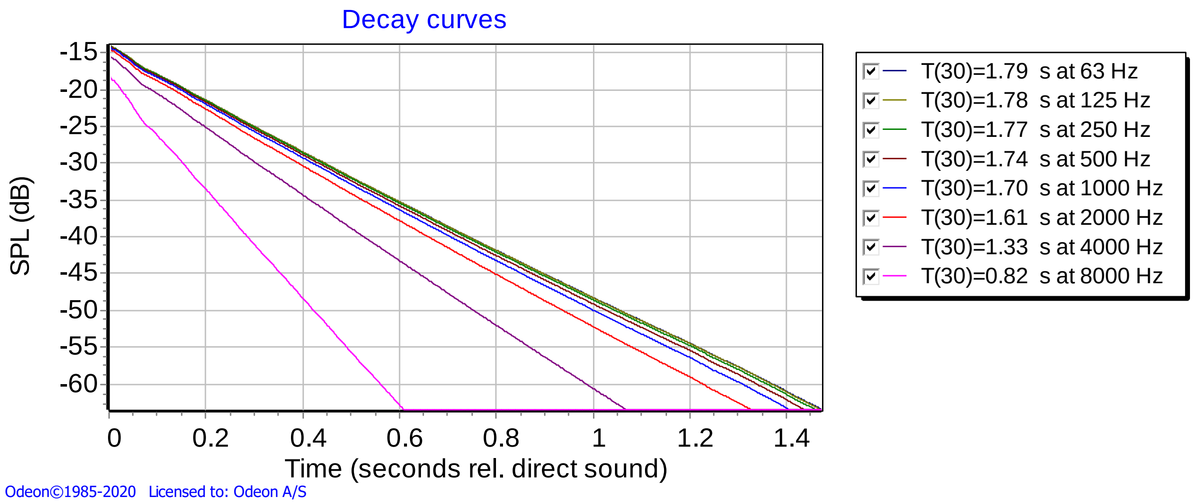

Figure 7: Decay curves for Condition 1 (Reflective surfaces) at Receiver 2.

The decay curves per octave band for Condition 1 at receiver positions 1 and 2 are shown respectively in Figure 6 and Figure 7. For **Receiver 1** (Figure 6), the decay curves do not follow an exponential decay, especially in the early part. This is due to the strong direct sound and the multiple strong early reflections which are definitely not representative of a diffuse sound field. In the later part of the sound field, the sound field becomes more diffuse and the decay is more exponential. Looking at **Receiver 2** (Figure 7), further away from the source, the decay curves are closer to straight lines, although a slight knee point is still visible at about 0.1 s. At this receiver location, the sound field is less influenced by early reflections and the decay is closer to an exponential decay. This is because all surfaces of the room are equally reflective, which favours more and more reflection directions far away from the source.

The linearity of the decay curves can be assessed by the non-linearity parameters ξ, calculated both for T_{20} and T_{30}, as well as the curvature C. ξ being above 10 ‰ means that the decay curve is not linear on the corresponding interval to estimate the decay parameter. For the decay to be properly exponential, C should ideally be below 10 %, while values above 15 % are not recommended [2, 5]. Table 2 reports these values at both receiver positions.

Table 2: Non-linearity parameters and curvature for Condition 1 (Reflective surfaces). The values indicating a non-exponential decay are coloured in orange.

Band	(Hz)	63	125	250	500	1000	2000	4000	8000
Receiver 1									
ξ (T(20))	(‰)	1.4	1.5	1.7	1.8	2	2.4	3.6	14.2
ξ (T(30))	(‰)	0.5	0.5	0.6	0.7	0.7	0.8	1.2	4.2
Curvature(C)	(%)	1.1	1.1	1	1	0.9	0.6	-1.5	-4
Receiver 2									
ξ (T(20))	(‰)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3
ξ (T(30))	(‰)	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.1
Curvature(C)	(%)	2.2	2.2	2.2	2.1	2.1	1.8	1.3	0.2

At all octave bands, the curves are overall sufficiently linear. Even at Receiver 1, the slope variations are small according to these indicators. This is because the calculation of T_{20} and T_{30} excludes the first 5 dB of decay, precisely in order to remove the influence of the direct sound, which is particularly strong for Receiver 1. The 8 kHz curve at Receiver 1 is the only one that deviates slightly in the early part, where T_{20} is calculated (indicated in orange in the table).

4.2. Condition 2: Absorbing ceiling

The non-exponential nature of the decay is more pronounced if the absorption properties are unevenly distributed in the room, which is the case of Condition 2 with an absorbing ceiling.

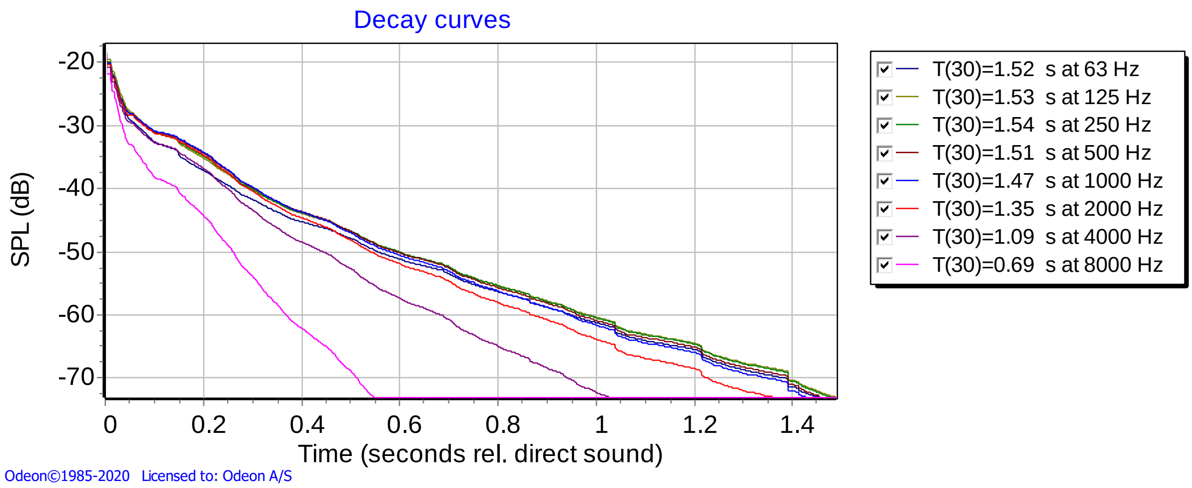

Figure 8: Decay curves for Condition 2 (absorbing ceiling) at Receiver 1.

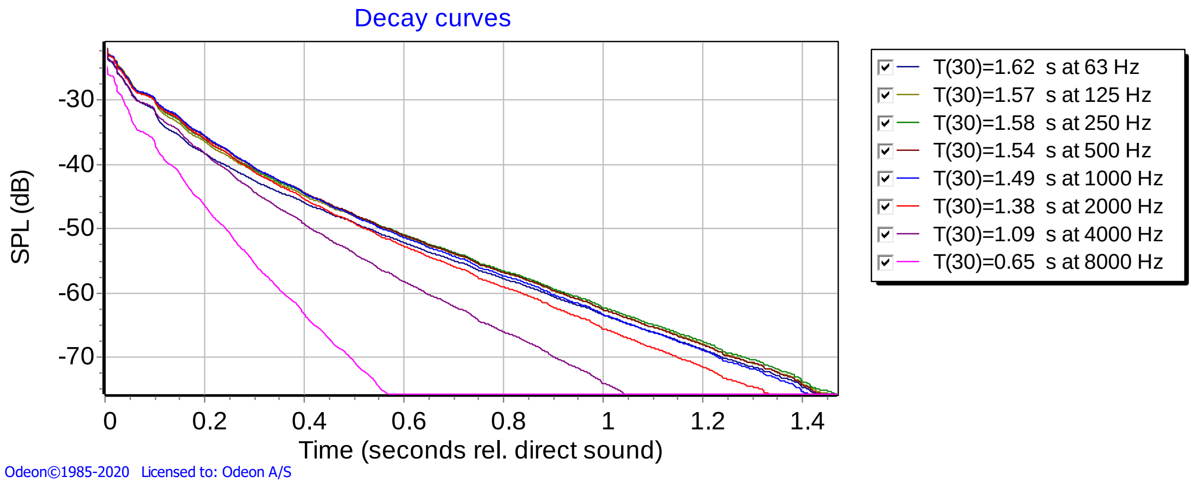

Figure 9: Decay curves for Condition 2 (absorbing ceiling) at Receiver 2.

The decay curves at Receiver 1 and Receiver 2 are shown in Figure 8 and Figure 9, respectively. At both receiver positions, the steep early part of the decay is due to the absorption of vertical sound components by the ceiling. The late part has a gentler slope and corresponds to the horizontal sound field, which is much less attenuated. Therefore, this second example does not follow the exponential decay expected from an ideal diffuse field. This is also visible in the non-linearity parameters, as shown in Table 3. The curves are slightly more linear at Receiver 2, but most parameters indicate a changing decay slope with time.

Table 3: Non-linearity parameters and curvature for Condition 2 (absorbing ceiling). The values indicating a non-exponential decay are coloured in orange. Curvatures between 10 % and 15 % are highlighted in yellow.

Band	(Hz)	63	125	250	500	1000	2000	4000	8000
Receiver 1									
ξ (T(20))	(‰)	37.9	21.2	18.9	17.2	16.3	18.1	35.4	83.2
ξ (T(30))	(‰)	31.6	22.9	20.4	16.3	13	9.2	11.2	27.1
Curvature(C)	(%)	38.6	31.2	28.1	23.1	19.1	12.9	5.4	5.5
Receiver 2									
ξ (T(20))	(‰)	26.4	15.7	12.3	8.1	6.1	4.6	2.9	8
ξ (T(30))	(‰)	24.5	21.7	19.4	15.9	13.3	10.8	6	3
Curvature(C)	(%)	29.3	27.7	26.1	23.1	20.2	18.2	12.4	4.6

5. Discrepancy between Sabine equation and ODEON results

Sabine's formula assumes a completely diffuse sound field in three dimensions, so it should be used with caution in real-life cases, where the sound field can be far from diffuse. This is the case of the studied rectangular room.

5.1. Condition 1: uniform absorption

Figure 10 compares different decay parameters calculated for Condition 1 (all walls with 10 % absorption) at the two receiver positions.

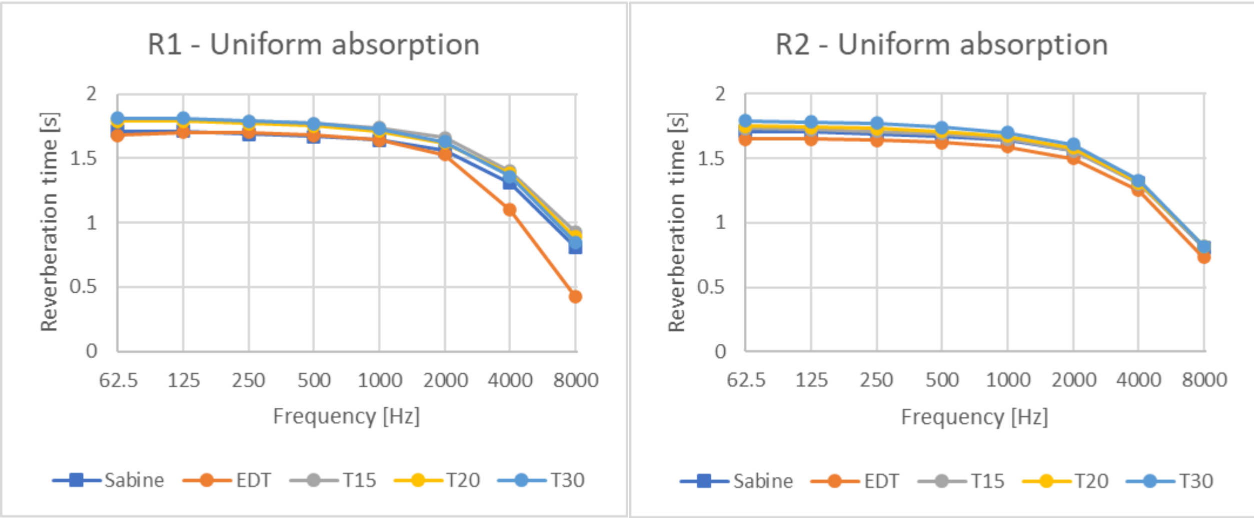

Figure 10: *Condition 1.* Comparison of decay parameters simulated by ODEON with the reverberation time calculated with Sabine formula.

At **Receiver 1**, the Sabine calculation is rather close to all decay parameters, except for EDT at 4 kHz and 8 kHz. The difference is due to the influence of strong early reflections that lead to a steeper decay in the early part – as shown by the decay curves in Section 4. For the rest of the curves, the decay is sufficiently linear to agree with Sabine's equation. At **Receiver 2**, where the sound field is mostly reverberant and the decay in dB is more linear, the Sabine equation results are in good agreement with all the decay parameters calculated by ODEON. Overall, the uniform absorption properties lead to a sufficiently diffuse sound field to make the use of the Sabine equation meaningful enough.

5.2. Condition 2: absorbing ceiling

Figure 11 shows the ODEON reverberation times compared with Sabine results for Condition 2 (ceiling with 90 % absorption).

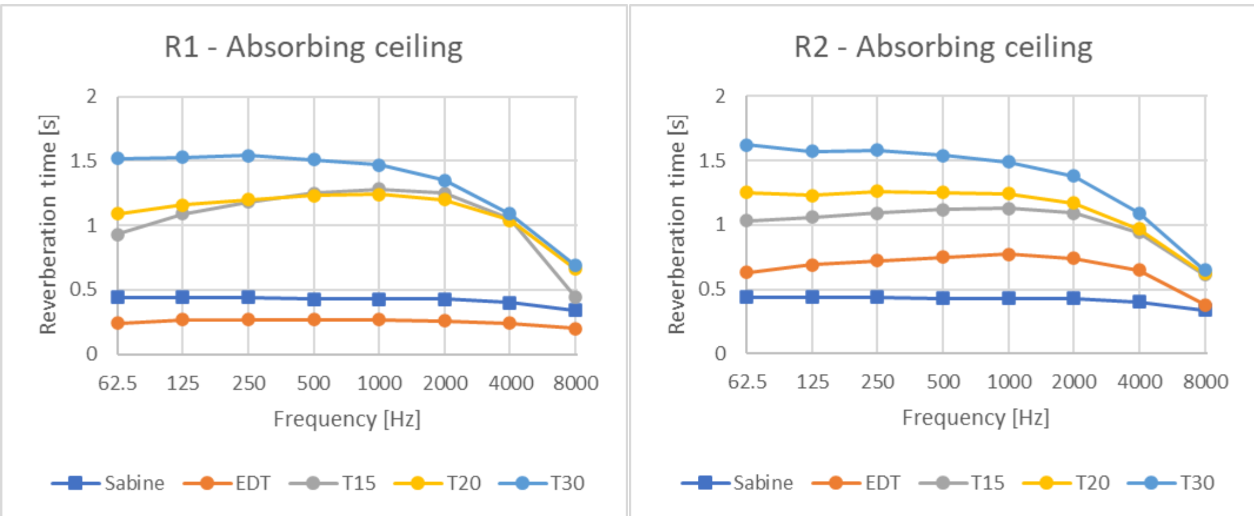

Figure 11: *Condition 2.* Comparison of decay parameters simulated by ODEON with the reverberation time calculated by Sabine formula.

The introduction of the extra absorption on the ceiling drastically reduces the Sabine reverberation time, down to about 0.5 s. However, the decay parameters simulated by ODEON differ greatly, not only from Sabine but also between each other.

For **Receiver 1**, EDT is the closest to the Sabine result, because it registers the decay due to the absorption by the ceiling, which is the dominating effect. The other decay parameters, T_{15}, T_{20} and T_{30}, also include the much slower decay in the horizontal plane, where very little surface absorption occurs. Overall, the three reverberation parameters lead to considerably higher values than predicted by Sabine. The strong knee-points between the *early part* and the *late part* of the decay can lead to inconsistencies when extrapolating the curves to calculate the reverberation times, so these values should be used with caution.

Similar conclusions can be reached with **Receiver 2**. However, the more reverberant nature of the sound field means that the decay curves are more linear, leading to slightly more consistent results between the different reverberation times. In particular, using a longer decay interval results in a larger reverberation time, as it includes a gradually larger part of the slow decaying horizontal field.

The difference between Sabine and late decay values such as T_{30} can be explained by the nature of the sound field, which is essentially horizontal in the late part. However, the Sabine equation assumes a 3D diffuse field. In addition, the absorbing ceiling has very little incidence on this horizontal field, because of virtually *no mixing* between the vertical and horizontal components. Therefore, the Sabine results are not to be trusted in this case. More generally, the decay parameters differ between each other because they describe different parts of the decay curve. They are also not representative of either of the two decay processes in play, as they are built under the assumption of an exponential decay. EDT remains a good descriptor of the fast-decaying early part, but the other parameters describe a mixture of both horizontal and vertical systems. T_{30} includes the larger proportion of the late slow-decaying part, so it is the parameter that describes it best, although it is still influenced by the early part.

5.3. Adding absorption can increase the reverberation time

Another counter-intuitive result is that adding absorption can lead to longer reverberation times, which contradicts Sabine's equation. As an example, we compare Condition 2 (absorbing ceiling) to an even more absorbing case where the absorption of the floor is raised to 20 %. The table below compares the resulting T_{30} at position receiver 2.

Table 4: Comparison of T_{30} at Receiver 2 between Condition 2 (absorbing ceiling) and added floor absorption of 20%.

Band (Hz)	63	125	250	500	1000	2000	4000	8000
Absorbing ceiling 90%	1.62	1.57	1.58	1.54	1.49	1.38	1.09	0.65
Added floor absorption 20 %	1.64	1.61	1.62	1.58	1.52	1.41	1.1	0.64

The additional floor absorption leads to a slight increase of T_{30} at all octave bands (up to 0.04 s at 125 Hz, 250 Hz and 500 Hz). Indeed, the floor only affects the fast early decay in the vertical direction – the decay then becomes steeper, whereas the late slow horizontal decay remains the same. This is illustrated in Figure 12 (the double slope effect is exaggerated). Therefore, the decay curve with added absorption gives more weight to the late horizontal field, which tends to increase late reverberation time parameters like T_{30}. In addition, the increased absorption reduces the steady-state sound pressure level, which is illustrated as a downward shift of the decay curve for Case 2 in Figure 12. It is possible that the lower sound levels will actually improve the acoustics of the room, despite the higher reverberation time.

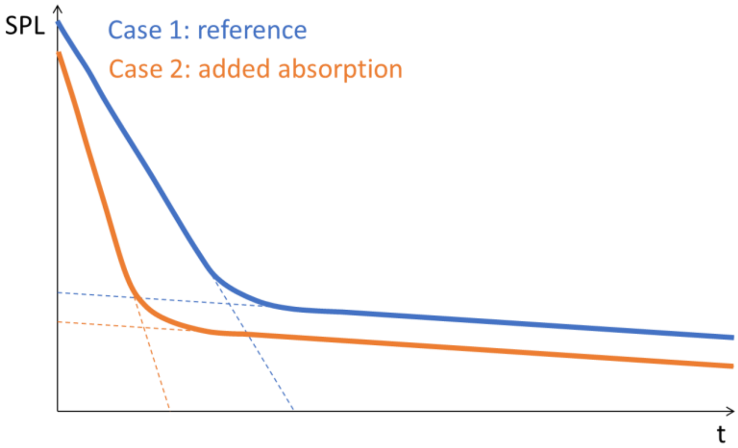

Figure 12: Effect of adding absorption on the floor. Schematic view of the decay curves.

5.4. Effect of added scattering

As discussed earlier, the lack of diffuseness explains the discrepancy between the Sabine theory and the ODEON simulations. The model with an absorbing ceiling can lead to a more diffuse field if more scattering is introduced [8]. This can be done by adding furniture in the room or increasing the scattering coefficient of the walls. Figure 13 shows the evolution of T_{30} (which was the value the furthest away from Sabine) with different scattering coefficients applied to all surfaces of the room.

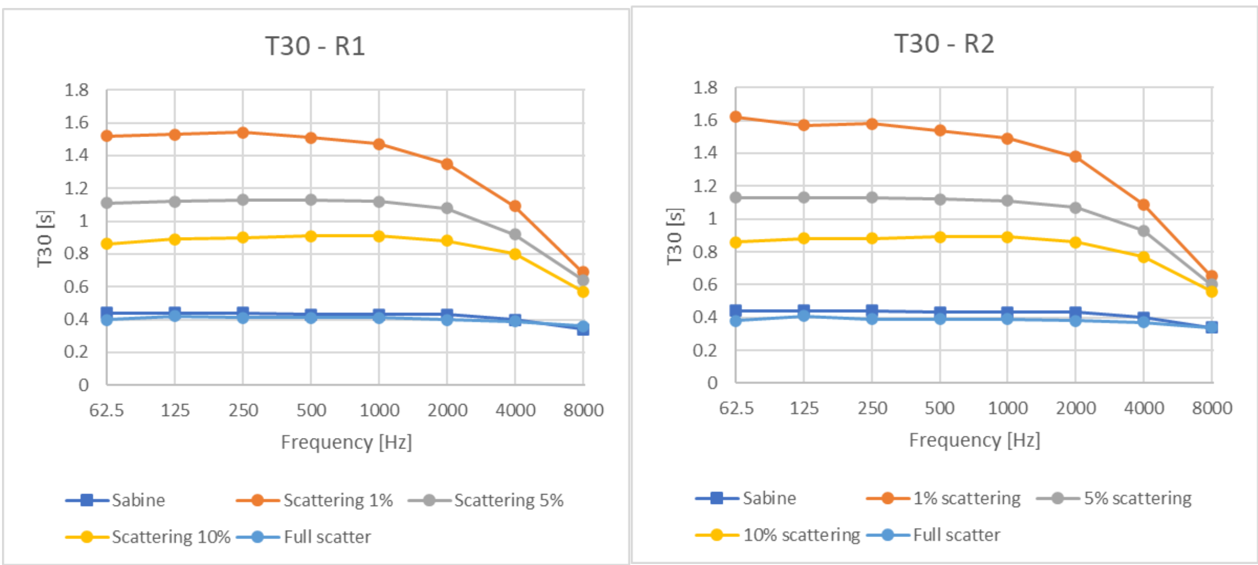

Figure 13: T_{30} simulated by ODEON for different amount of scattering, compared with the reverberation time calculated using the Sabine formula. The higher the scattering, the smaller the difference between simulations and Sabine.

Similar results are obtained for the two receiver positions. Increasing the scattering coefficient leads to a lower T_{30}, because more and more rays hit the ceiling and are thus attenuated, which amplifies the decay. It is worth noting that the 10 % scattering case still corresponds to relatively low scattering, but it results in significantly lower T_{30} values compared with the initial setup (1 % scattering). This illustrates that introducing just a little more scattering has a strong influence on the calculation. Finally, when the scattering is set to "Full scatter" (Room Setup menu), the sound field becomes largely diffuse and the obtained T_{30} is in agreement with the Sabine theory.

CAUTION! This last example simply illustrates the missing conditions to fulfil the Sabine assumptions. If the sound field is not diffuse in the room under study, the Sabine equation should be avoided in any case.

6. Differences between simulation and reality

Rectangular rooms are prone to discrepancies between simulations and measurements. The main issue is that the ODEON model might be "more perfect" than reality, where the walls are exactly parallel and they are modelled as too smooth surfaces.

It is possible that the walls of the rooms are not as flat as in the model, or that additional objects, such as furniture, were excluded from the model for simplicity. These can be accounted for by increasing the scattering coefficient of the walls in ODEON (this is why we do not recommend setting scattering coefficients to 0). However, as shown in Section 5.4, the simulation results can be very sensitive to the scattering coefficient of smooth surfaces.

The effect of the parallelism between surfaces is illustrated in the example below, where one of the side walls is tilted towards the inside of the room (see Figure 14). The top edge of the wall is brought forward by 5 cm, which results in an angle of 1° between the two side walls. The ceiling is 90 % absorbing in both models. The small tilt has virtually no effect on the reverberation time calculated with Sabine's equation, because the geometry of the model is almost unchanged.

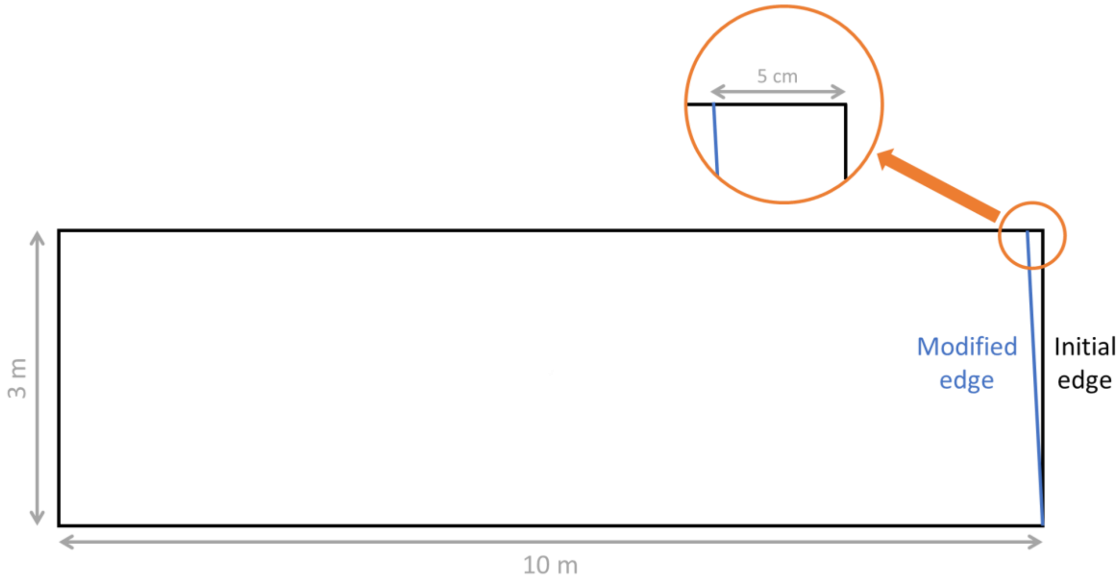

Figure 14: Drawing showing the geometry with a tilted wall. Note: the tilt is exaggerated in the drawing.

Figure 15 shows T_{30} for both models and the two receiver positions, compared to the Sabine reverberation time for the perfectly-angled room. The behaviour is the same at both receiver positions. Tilting the wall leads to a lower T_{30}, thus bringing it closer to the Sabine result. The tilted wall has a similar effect to increasing scattering, as more rays are reflected towards the absorbing ceiling, which leads to a faster decay than in the perfect rectangle case. The difference with an increased scattering coefficient is that the redirection is more deterministic, which leads to less diffuseness. This explains why T_{30} remains relatively high, compared to the high scattering results from Section 5.4. An interesting observation is that increasing the tilt from 5 cm up to 20 cm does not affect T_{30}, because the process is mostly left unchanged, due to the low height of the room: rays tend to be redirected towards the floor, reflected towards the ceiling and absorbed there.

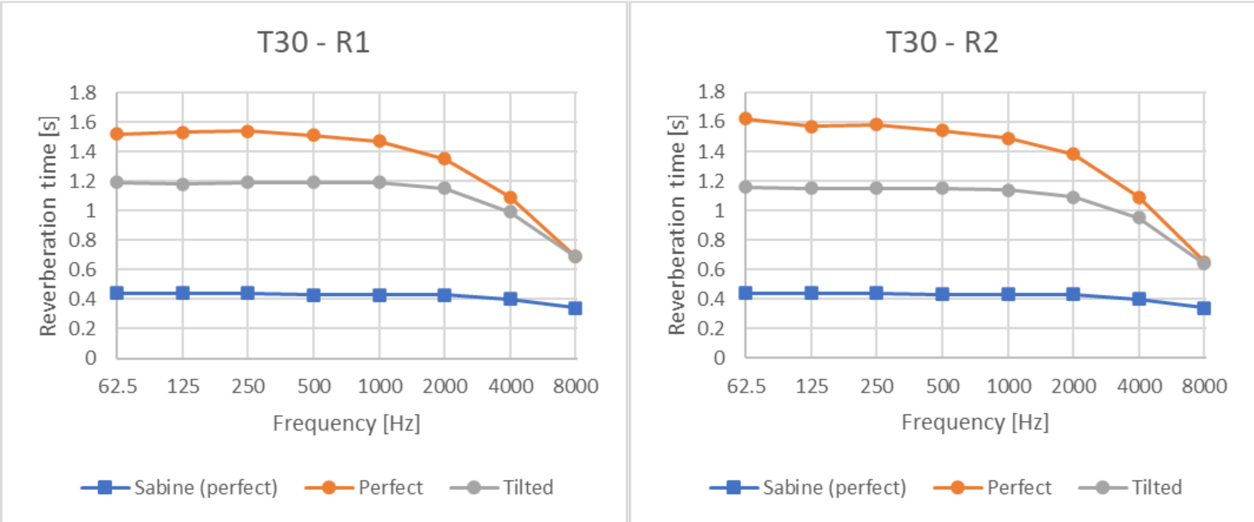

Figure 15: The effect of tilting one wall in the overall perfectly right-angled room. As mixing between the three dimensions is achieved, the ODEON simulated T_{30} decreases.

This example illustrates that any imperfection in the geometry can lead to significantly different results compared to a "perfect" numerical model. In that sense, the reality lies somewhere between the ODEON results and the diffuse Sabine case, depending on the actual amount of scattering.

Another key aspect is the flatness of the room, which favours grazing incidence on the floor and the ceiling. This makes the result dependent on the accuracy of the angle-dependent absorption model [7]. If the absorption properties of the floor and the ceiling are not accurate in the model, the calculated results may not be realistic.

7. Sensitivity to input data

We have already shown that the simulation is sensitive to the lower end of the scattering coefficient scale. This is because changes in the scattering coefficient should be understood in a *relative* scale. For example, if the scattering coefficient is raised from 5 % to 10 %, it is multiplied by 2, which has a considerable effect on the calculation. In contrast, raising a scattering coefficient from 90 % to 95 % corresponds to a multiplication of scattering by 95/90 =1.06, thus having very little effect.

This section focuses on the sensitivity to the absorption coefficient. We take the absorbing ceiling example as a reference case (the walls and the floor are 10 % absorbing; the ceiling is 90 % absorbing). We study three "small variations":

- Ceiling set to 95 % absorption,
- Floor set to 5 % absorption,
- One side wall set to 5 % absorption.

The other surfaces are left untouched.

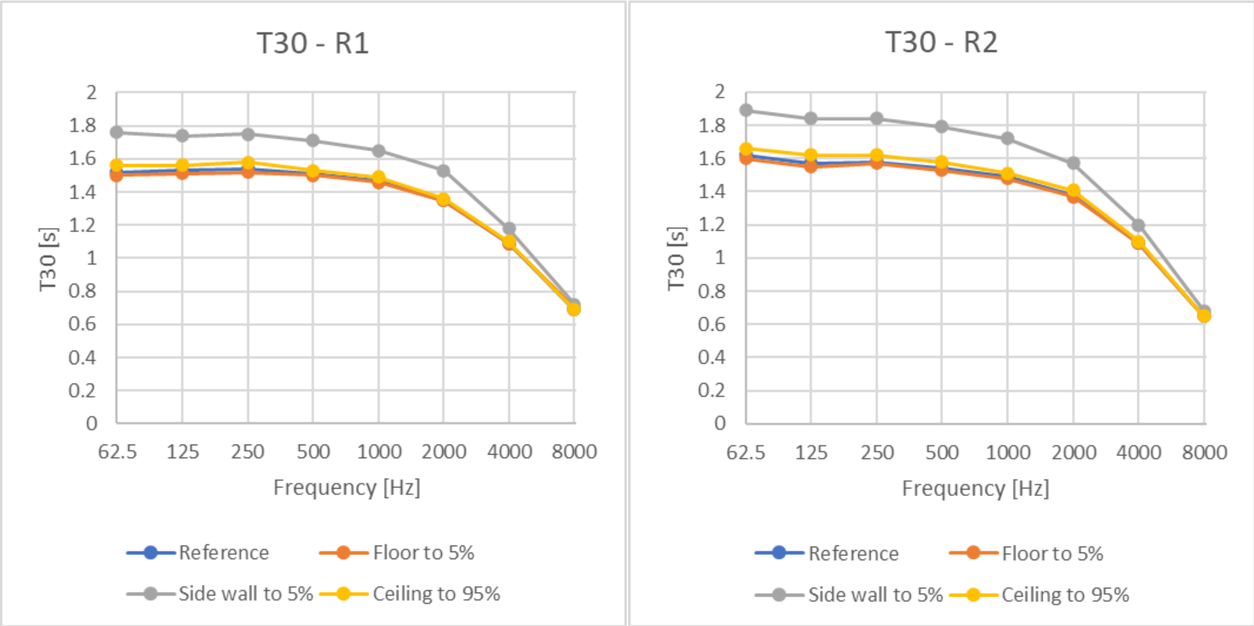

Figure 16: Various changes in absorption on different surfaces. Influence on T_{30} at receiver positions R1 (Left) and R2 (Right). Comparisons are made with the reference case (ceiling 90 % absorbing, all other surfaces 10 % absorbing).

Figure 16 reports T_{30} at both receiver positions. The behaviour is similar in both graphs. Changing the ceiling or the floor has very little effect on T_{30}. As explained before, the ceiling leads to the absorption of early vertical rays, while the T_{30} value is mostly due to the slow decaying field in the horizontal direction. Therefore, the changes in the floor and the ceiling have very little influence on T_{30}. Conversely, changing the absorption of one side wall from 10 % to 5 % has a considerable effect, as T_{30} is raised by up to 0.2 s. This also illustrates that the simulation results are particularly sensitive to the properties of reflective surfaces, as the reflected rays still carry considerable amounts of energy.

In conclusion, the simulation examples show a great sensitivity of the simulation results to certain aspects of the model, including:

- Scattering coefficient of flat surfaces (i.e., low scattering values);
- Absorption coefficient of reflective surfaces (i.e., low absorption values);
- Absorption coefficient of exposed surfaces (i.e., surfaces which are hit by a large number of rays).

This is problematic because there is already much uncertainty about the input data, for instance in terms of random absorption coefficient [9]. Any inaccuracy in the absorption or scattering data has a strong impact on the simulation results, especially because only a few materials are used in the model. If there were many materials in the model, one should expect errors on input data to average out.

8. Conclusion

Rectangular rooms are a good example of challenging rooms to study and to model in ODEON. Uneven dimensions and uneven absorption lead to an atypical sound field, which does not decay exponentially. This means that traditional room acoustic tools and methods, such as the Sabine equation or the calculation of reverberation times by extrapolation, should be used with caution.

Furthermore, the studied models proved sensitive to various input data, including the scattering coefficient of flat surfaces, the absorption coefficient of reflective surfaces and the geometry (wall parallelism). As a result, the ODEON output might also be unstable or unreliable. This may be even more true when approximations such as absorption at grazing incidence form a considerable part of the calculation.

Certain classes of rooms will therefore lead to uncertain results, whether with "traditional" approximate methods (such as Sabine formula) or ODEON simulations. These include the following aspects:

- Simple geometries: few surfaces, perpendicular or parallel surfaces.
- Uneven dimensions (e.g., flat rooms favouring two-dimensional sound fields).
- Low scattering cases: smooth surfaces, empty rooms.
- Uneven absorption: existence of both regions with very high absorption and very low absorption. The results are particularly sensitive to the absorption data of reflective surfaces.

In these cases, the sensitivity of the calculation makes it fundamentally difficult to properly simulate acoustic measurements with ODEON. Therefore, we can expect differences between measurement and simulation data for such rooms.

9. Guidelines for rectangular rooms

We have shown that modelling a simple rectangular room in ODEON presents multiple challenges. Although the simulation results are uncertain, the following guidelines can help to ensure more reliable calculations:

- Use a large number of rays to properly simulate the late part of the decay.
- Pay attention to the aspect of the decay curves to check if the decay is non-exponential.
    - By visual inspection: bended decay curves.
    - By comparing the decay parameters: differences between T_{15}, T_{20} and T_{30}.
    - By checking the non-linearity parameters ξ: ξ above 10 ‰.
    - By checking the curvature C: C above 15 %.
- If the decay is non-exponential, do not trust Sabine's equation.
- Caution! The model can be extremely sensitive to input data, and some of this data can be uncertain:
    - Parallel walls: are they exactly parallel in reality?
    - Scattering coefficient of flat surfaces.
    - Absorption coefficient of reflective surfaces.
- It could be a good idea to have some reference measurements to compare with in order to adjust the input data.

In addition, we have seen that such rectangular rooms are prone to unwanted acoustical effects such as flutter echoes. A solution can be to make the space more diffuse, which can be achieved in various ways:

- Room geometry:
    - Avoid large flat surfaces.
    - Avoid parallel surfaces and perpendicular surfaces
    - Favour rooms with not too extreme aspect ratios (for instance, [6] recommends aspect ratios ideally between 1.15 and 1.45).

- Distribute the absorption in the room.
- Add scattering, for instance by adding objects or diffusers.

References

[1] M. R. Schroeder and K. H. Kuttruff, “On frequency response curves in rooms: Comparison of experimental, theoretical and Monte Carlo results for the average frequency spacing between maxima,” *J. Acoust. Soc. Am.,* vol. 34, pp. 76-80, 1962.

[2] Odeon A/S, ODEON Room Acoustics Software, manual, Denmark, 2021.

[3] H. Kutruff, Room Acoustics, London: Applied Science Publishers, 1973.

[4] ISO 3382-1, “Acoustics - Measurement of room acoustic parameters - Part 1: Performance spcaes”.

[5] ISO 3382-2, “Acoustics - Measurement of Room acoustic Parameters - Part 2: Reverberation Time in Ordinary Rooms.”.

[6] J. H. Rindel, “Preferred dimension ratios of small rectangular rooms,” *JASA Express Lett.,* vol. 1, no. 2, p. 021601, 2021.

[7] E. Nilsson, “Decay Processes in Rooms with Non-Diffuse Sound Fields. Part I : Ceiling Treatment with Absorbing Material,” *Building Acoustics,* pp. 39-60, 2004.

[8] E. Nilsson, “Decay Processes in Rooms with Non-Diffuse Sound Fields. Part II : Effect of Irregularities,” *Building Acoustics,* pp. 133-143, 2004.

[9] M. Nolan, M. Vercammen, C.-H. Jeong and J. Brunskog, “The use of a reference absorber for absorption measurements in a reverberation chamber,” 2014.