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Double slope decay rooms: the influence of coupling aperture location on reverberation according to seat location

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Abstract

The construction of performance spaces with variable acoustics is part of a growing tendency among acousticians. One way of varying the acoustics of a room is using a coupled acoustic chamber that can be located around the stage area or along the sidewalls. The coupling area can substantially change the reverberation time of the hall, depending on volume and the ratio of absorption between the chamber and the main room. Coupled rooms are common for having a double slope decay curve. It is also common that the doors of the chamber are located in a balcony area where there are audience seats. Therefore, it is possible that with the same coupling area, different listener positions may have a different perception of spatialization due to proximity of the acoustic chamber. Also, if a room has several coupling doors, the location and sequence of opening may interfere in the acoustic perception of that space. The aim of this study is to compare the variation of reverberation time in a coupled volume concert hall in several seats location by changing the location of the coupling areas. A concert hall was simulated in Odeon with 12 different coupling areas by means of 136 doors. Two scenarios were analyzed: one, where the apertures are progressively opened close to the audience, another, where the openings are opened far from the audience seats. Results show that the location of the coupling areas promotes a variation in reverberation time in different seats positions and listeners may possibly perceive it.

Keywords: Coupled rooms, Double slope decay, reverberation chamber, variable acoustics

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1 Introduction

Theatres and concert halls with variable acoustics are a good opportunity for architects, designers and acousticians to project a performance space that can be of use for a variety of spectacles. Even for concert halls, acoustic variability may improve the hall ability to adequate several genres of musical performance, from solo instruments and small ensembles to great orchestras. Repertoire is also benefitted from such variability; some authors [1] [2] propose different reverberation times for different periods of music composition. One way of varying the acoustics of a concert hall is to add a reverberation chamber around the room, which if properly coupled to the main room may provide acoustic variability.

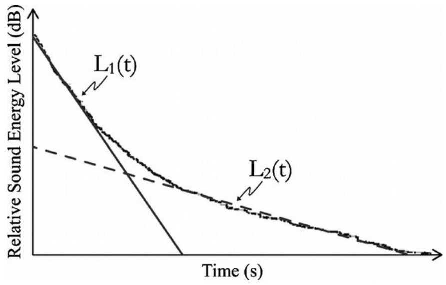
Coupled rooms are known to produce a double slope energy decay ratio, which can provide good clarity and yet reverberance [2]. Many concert halls were made following this proposition and some of their coupling aperture are located next to audience seats, for example, next to lateral balconies [2]. In the literature there are almost no indication of how listener position may be acoustically influenced by seating right next to an opened door to a reverberant chamber. Therefore, it is possible that with the same coupling area, different listener positions may have a different perception of spatialization due to the proximity of the acoustic chamber. Also, if a room has several coupling doors, the location and sequence of openings may interfere in the acoustic perception of that space. The aim of this study is to compare the variation of reverberation time in a coupled volume concert hall in several seats locations by changing the location of the coupling areas.

2 Background

Coupled rooms have been extensively studied along the years [3]. Many studies have been trying to understand its physical aspect [4] and others are trying to propose mathematical models to better describe the acoustic influence of secondary rooms coupled to a main room [3] [5].

It is a common sense that the descriptor T30, used for the calculation of reverberation time, is not the best descriptor in the case of double decay curves mainly because the decay is not truly exponential [6]. Therefore, instead of a straight line, the decay is similar to a bending curve as seen on Figure 1. Due to the time interval used to calculate reverberation time with T30 (from -5dB to -35dB), the bending point of the curve could be somewhere in the end portion or even outside that proposed interval, leading to an erroneous time calculation.

Standard ISO 3382-1 [7] proposes two parameters that may indicate if the curve may or may not have an exponential decay, but they do not quantify the double slope decay. Therefore, another approach to study coupled rooms is the attempt to quantify the double slope effect (DSE) and find a descriptor that would define the characteristics of the double-sloped curve. Other descriptors used to calculate reverberation time such as T10 and T15 and LDT (Late decay time), which use different interval times to calculate reverberation time, were used as a means to establish ratios that could describe the double slope. Ratios such as T30/T15, T30/T10, LDT/EDT and later LDT/T10 were proposed [8]. But in order to correctly physically describe the double slope decay, mathematical models based on Bayesian statistics have been having much better results [9].



Source: (Bradley Wang, 2010)

Figure 1: representation of a double slope decay curve

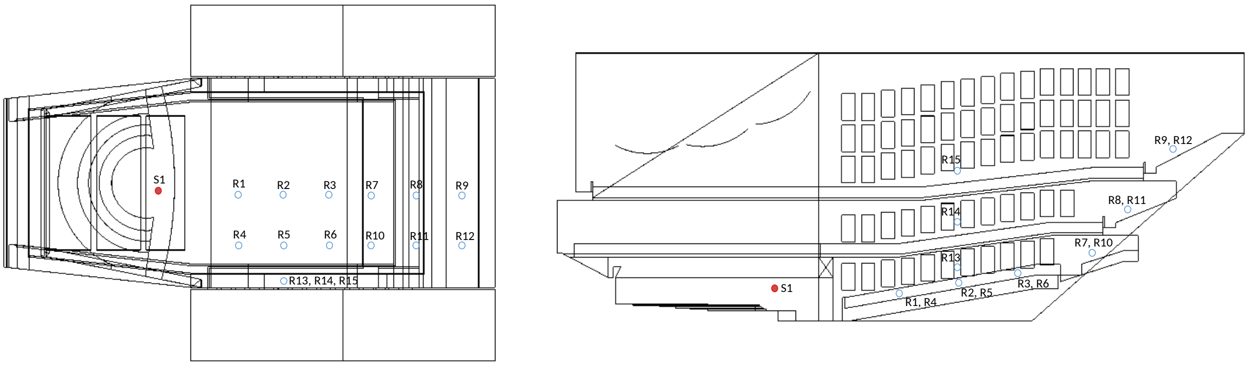
Subjective studies have also been made [10] indicating that subjects could differentiate double sloped curves from exponential ones. Later, other studies [8] attempted to indicate that subjects have a preference over curves tending to an exponential decay and the more bended the curve, the lesser the preference. Also, in their later research, Bradley and Wang [8] proposed as a future study, to verify the influence of the location of apertures and their influence over the audience area.

3 Methodology

In order to understand the influence of the location of apertures in listener position, a computer model of a concert hall was built and an acoustic simulation was performed in Odeon Room Acoustic software version 13. The following sections describe the model and simulation performed. This research took as a starting point the research proposed by Bradley and Wang [8] regarding volume ratio of the main room and the acoustic chamber and the acoustic absorption ratio between main and secondary rooms.

3.1 Computer Model

It was chosen, as a base model, a real concert hall in order to have real dimension proportions. The chosen room was Malmö Live in Sweden. The room is a rectangular concert hall with no variable acoustics, therefore, no means to vary its acoustics. Besides room proportions, a real concert hall as a starting point, would also be a guidance to the choice of materials. To promote the needed acoustic variability, a lateral reverberation chamber on both sides of the audience was designed as seen in Figure 2.



Source: (Authors, 2016)

Figure 2: Top and side views of the modeled room

To couple the reverberation chambers to the main room, 68 doors in each chamber, totalling 136 doors were added to the model. Each door has an area of 2 m^2. Table 1 summarizes data of dimensions, areas and volumes for both rooms.

Table 1: Data for dimensions and volume for both rooms

Main room dimensions	51.5 x 21.8 x 20 m (LxWxH)
Chamber dimensions	31.9 x 7.5 x 20 m (LxWxH)
Main room volume	16,292.8 m3
Chambers volume	7,889.8 m3
Total volume	24,182.6 m3
Main room area	4,540 m2
Total openings area	272 m2
Volume ratio	48,4%
Depth of the chambers	7.5 m

It was added one omnidirectional sound source on stage and 15 receivers position along the hall. Receiver positions were chosen in order to cover most sections of the audience such as front, middle and back stalls, front, middle and back center balconies, both middle and lateral ones. It was also positioned 3 receiver points, one in each lateral balcony, right in front of a possible coupling aperture. Sound source and receivers positions can be seen in Figure 2.

3.2 Materials assigned

Most of the materials chosen for this model were based on the actual hall with exception of the ceiling which was applied an absorption coefficient to reduce reverberation time to a desired value. Table 2 shows the absorption coefficient of the materials assigned to the model. In the actual hall, only the balconies use a slotted panel, but in the modelled hall, this material was also used on the walls in the back of the hall and in the back of the audience area behind the orchestra stage. This approach helped reducing the reverberation time of the hall to about 1 second in 500Hz when all doors to the acoustic chamber are closed.

The average absorption coefficient of all materials (Avg. Alpha) was calculated by arithmetic averaging the absorption coefficients in all octave bands. Then the total absorption was calculated by multiplying the averaged alpha with the material area.

Table 2: Materials and absorption coefficients used in the model

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz	Area	Avg. Alpha	Scattering	A	A main
Wood	0.10	0.10	0.07	0.05	0.06	0.06	0.06	0.06	1,866.97	0.07	0.5	130.69	2,076.86
Slitted Panel	0.16	0.49	0.69	0.63	0.43	0.27	0.19	0.18	800.84	0.38	0.3	304.02	**A sec**
Stage	0.19	0.19	0.14	0.09	0.06	0.06	0.05	0.05	246.79	0.10	0.05	25.60	74.63
Ceiling	0.40	0.40	0.57	0.72	0.69	0.66	0.46	0.26	1,055.34	0.52	0.5	548.78	**Abs Ratio**
Audience	0.72	0.72	0.79	0.83	0.84	0.83	0.79	0.79	1,353.75	0.79	0.7	1,067.77	0.04
Concrete	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	3,420.63	0.02	0.3	55.59	
Chamber Doors	0.10	0.10	0.07	0.05	0.06	0.06	0.06	0.06	272	0.07	0.5	19.04	

The total absorption of the main room was calculated by summing the total absorption of each material in the room. The same was applied to the reverberation chamber. The absorption ratio proposed by Bradley and Wang [8] was also calculated by dividing the total absorption of the chambers by the total absorption of the main room. The ceiling material was used and properly adequate in order to provide the same absorption ratio as in Bradley and Wang's research [8].

3.3 Variation of openings

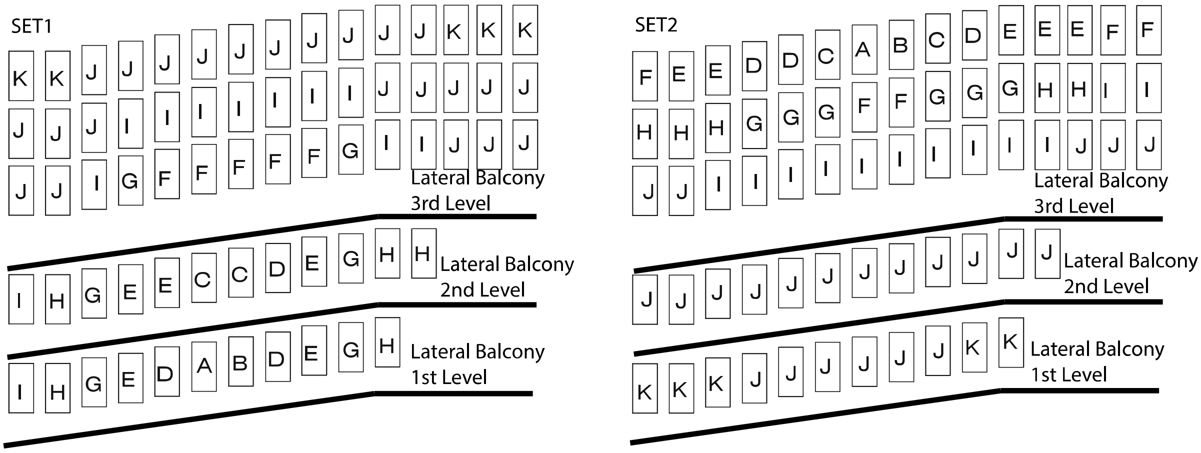
It was simulated 12 different openings in order to understand the influence of the coupling apertures in different seats locations. Each simulation will be called a MODEL with a letter from A to K. MODEL ZERO is the room with all doors closed and therefore no coupling. Table 3 shows, for each model, the number of opened doors, coupling area and percentage of coupling aperture. Note that the doors are always a pair number and represent the total number of doors opened in both chambers. So when there is a model with 2 doors opened, it means that there is one door in each chamber opened and the position of the opened doors are mirrored, so they open in the same position on both sides of the main room.

Table 3: Simulated models with their respective openings

MODEL	Number of doors	Coupling Area(m2)	Opening (%)
ZERO	0	0	0
A	2	4	0,1
B	4	8	0,2
C	8	16	0,4
D	14	28	0,6
E	24	48	1,1
F	34	68	1,5
G	46	92	2,0
H	56	112	2,5
I	80	160	3,5
J	100	200	4,4
K	136	272	6,0

Aperture opening is calculated by the percentage of opening area over the entire main room area. It was also performed two Sets of simulation, each Set with the 12 models already described. The difference between those sets is the position of the opened doors. Set 1 starts opening the coupling doors from the first balcony to the top. Set 2 starts opening the coupling doors from the ceiling going down. Both aperture Sets can be seen in Figure 3.

It is important to notice that in Set 1, the openings start with model A door, which is in front of a lateral balcony receiver position.



Source: (Authors, 2016)

Figure 3: Sets of aperture location

Set 2 opening starts with the door from model A on the middle top of the available doors, far from any receiver. To make clear, when model B doors are opened, so it is model A's door. When model C doors are opened so it is models A and B doors and so on, thus increasing the coupling aperture in each consecutive model according to Table 3. That way, on Set 1, receivers on the lateral balcony will be right in front the opened doors when model F, with 1.5% of coupling area is fully opened. On set 2, the same 3 receivers on the lateral balcony will be in front of the opened doors only in model J, with 4.4% of the coupling area opened.

3.4 Acoustic Parameters

Analyzed acoustic parameter for this study will be reverberation time described by the descriptor T30, which is the time of the energy decay computed from a line of a linear regression of the energy decay curve starting at -5 dB to -35 dB and then multiplied by 2. Knowing that T30 may not be a good descriptor for double slope decay curves, the Schroeder curve will also be analyzed.

4 Results and Discussion

Results for the simulation of Set1 can be seen on the graphics of Figure 4. The graphics show the variation of reverberation time by octave band for point 1 to 15 and sound source 1.

One of the characteristics of reverberation time in single rooms with no coupled rooms, besides the exponential decay, is the homogeneity of reverberation across the room. When analysing the graphics, it is very noticeable the disparity of reverberation time across receiver points specially at low coupling apertures up to model H, with 2.5% of coupling aperture. From model I and up, reverberation tends to be a lot more homogeneous across the room, with little variation. Models A to D also get the attention for points 13 (models A to D) and 14 (models C and D). Due to the proximity of those points to the coupling aperture it seems plausible to assume that somehow the perception for those receivers will not be the same when compared to the rest of the room.

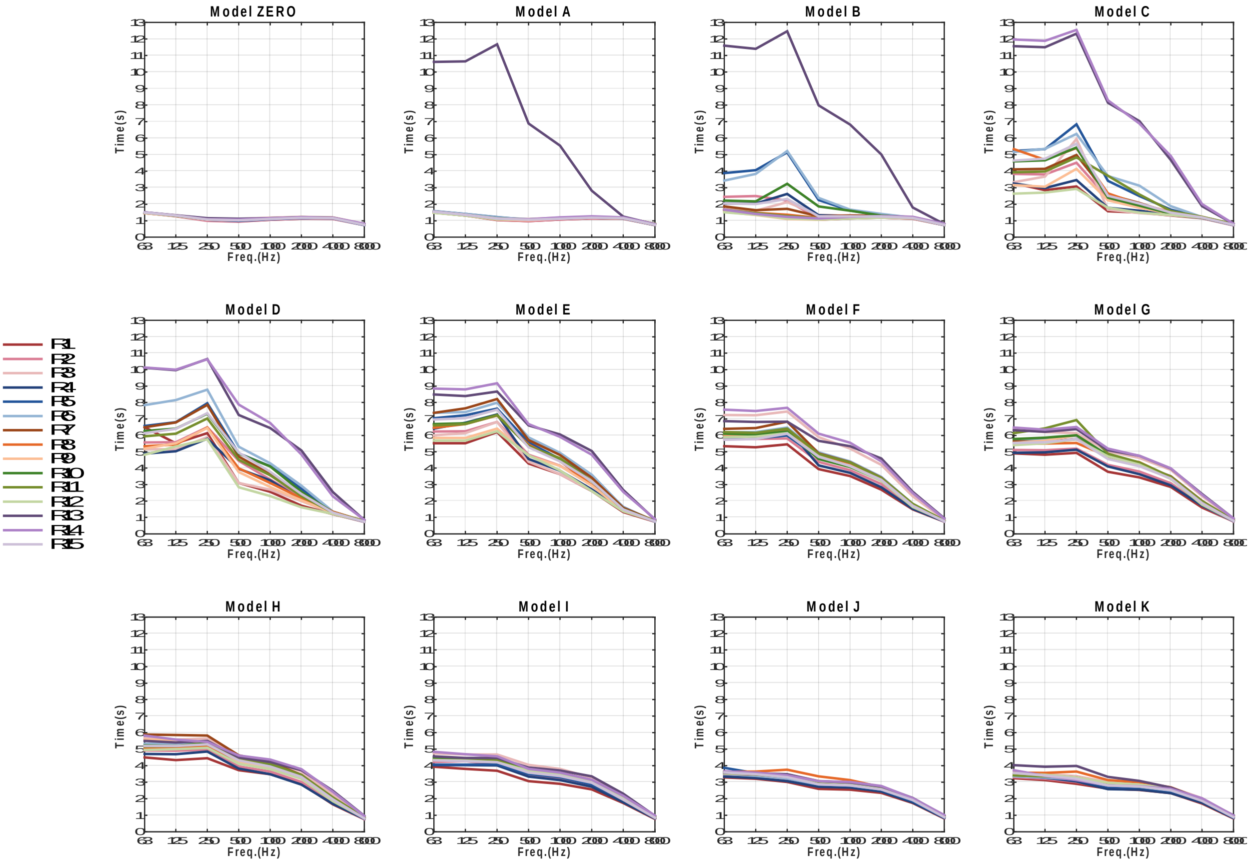


Figure 4: results of reverberation time (T30) by frequency in octave bands for SET1

Models D to H show a great variety of T30 across the room. The greater disparity is at low frequency. In order to better understand this great difference, the Schroeder plots were also analysed. Figure 5 shows the comparison of points P2 and P14. Graphic (a) show the comparison of both points in model D and Graphic (b) show both points in model J. Values of T30 for both points on both models are also in the graphic. On model J, the difference of T30 for both points is only 0.3s, approximately the JND for RT according to some latest research [11].

When looking at graphic (a) of Figure 5, it is clear the double slope decay. It is also clear that the bending points of the curves are in different energy levels and time. Receiver 14's curve tends to reach more into an exponential decay curve then Receiver 2 and this is probably caused by the proximity to the apertures as shown by Xiang *et al* [12]. However, Xiang *et al* [12] found a small difference between decay times between the curves, as the receiver gets distant from the coupling aperture. That is probably due to the fact that their research used a slit simulating a real aperture. When the apertures are much wider than a slit, like this research with actual doors, the effect is different as seen on Figure 5 (a). Also, it seems that both curves have longer decay time then the values proposed by T30. What is so far not clear is if subjects would clearly notice the difference between both curves, especially when the sound source stops, as in a final orchestra chord. Graphic (b) of Figure 5 shows that with a bigger aperture size, in this case 4.4% of aperture, the curves are clearly more like an exponential decay. So far, subjective preferences [8] show that subjects have a preference for exponential curves over double slope decay curves.

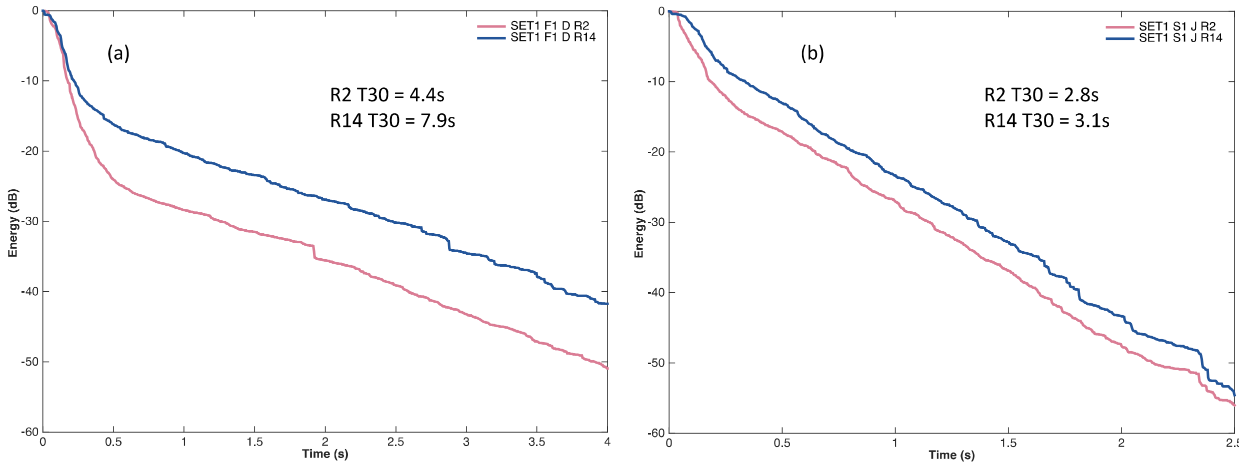


Figure 5: Decay curve comparisson between models D and J

Results for the simulation of Set2 can be seen on the graphics of Figure 6. The graphics show the variation of reverberation time by octave band for point 1 to 15 and sound source 1.

The analysis of the graphics shows that the difference found before in points 13 and 14 no longer exists. The great disparity in T30 values starts on model C and continues up to model H. Only in model I to K the reverberation is more homogeneous and probably there is more chance that the perceived reverberance is equal across the room. From this analysis, it is possible to establish as a guideline, that the coupling aperture should not be less then 2.5%. Values below that will increase the risk of a variety of reverberation perception around the room in different seats locations.

Due to the small amount of research regarding the subjective perception of double slope decay, it is hard to assume if the differences found on lower aperture sizes will in fact have an impact on the perception of reverberance. Therefore, this is a field for future researches.

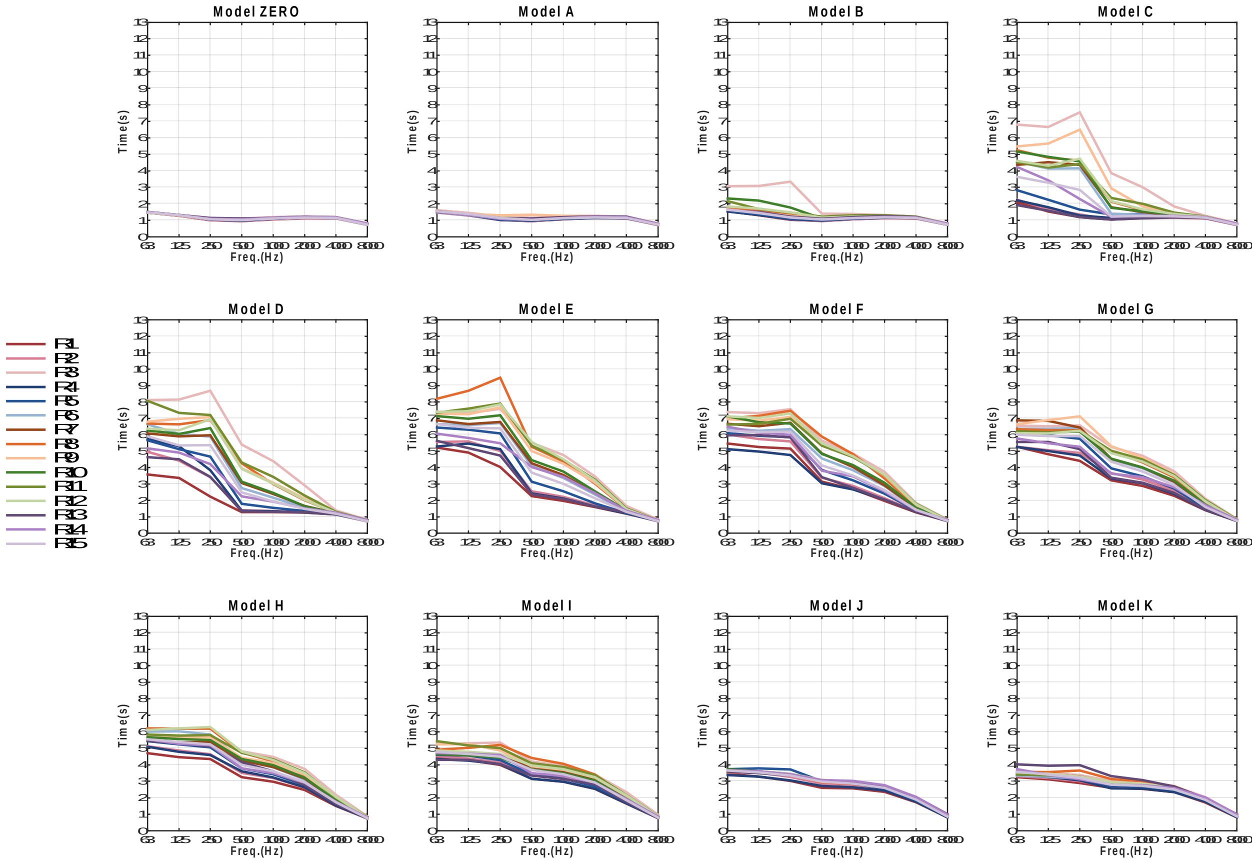


Figure 6: results of reverberation time (T30) by frequency in octave bands for SET2

5 Conclusions

A computer simulation was done to investigate the influence of location of the coupling apertures in a hall with a reverberation chamber coupled to it. It was found that for smaller apertures, receiver points in front of an opened door might perceive reverberation time differently from other receivers across the room. For apertures up to 2.5%, reverberation across the room is very irregular and that should be the minimum aperture to be considered as a starting point. It also seems that opening all the possible apertures in front of audience seats first, with openings closer to the sound source, tends to better balance reverberation time with apertures of 2.5% and up. Analysing the Schroeder curves of two points, one closer to the apertures and the other far from the aperture it was clear the difference in their decay curves. The closer the receiver is to the aperture, the more similar is the curve to an exponential decay. On smaller aperture ratios there is a chance that receivers in different room locations will perceive different sensations in reverberation. Since subjective preference tends to be to exponential decay curves over double slope decay curves, apertures of 2.5% should be the minimum starting point as a recommended value of aperture ratio.

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