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Evaluation of Reverberation Time Models with Variable Acoustics

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ABSTRACT

Reverberation time of a room is the most prominent parameter considered when designing the acoustics of physical spaces. Techniques for predicting reverberation of enclosed spaces started emerging over one hundred years ago. Since then, several formulas to estimate the reverberation time in different room types were proposed. Although validations of those models were conducted in the past, they lack testing in a space with a high granularity of controllable absorptive and reflective conditions. The present study discusses the reverberation time estimation techniques by comparing various formulas. Moreover, the reverberation time measurements in a variable acoustic laboratory for different combinations of reflective and absorptive panels are shown. The values calculated with the presented models are compared with the ones obtained via measurements. The results show that all formulas predict reverberation time values inaccurately, with an average error of 16% or larger. Among the analyzed models, Fitzroy's formula gives the smallest error.

1. INTRODUCTION

Reverberation is considered as one of the most important qualities of sound within the physical space [1–3] and therefore central in designing acoustics of halls and rooms. The first attempt to invent a theory to predict the reverberation time value of a given space was made by Sabine [4], who introduced a formula based on experimental results. Over the decades, many improvements were made to his model to allow more accurate predictions for spaces with both uniformly and unevenly distributed absorption [3, 5, 6]. However, studies show that in many cases those formulas do not give results close enough to measured reverberation time values to be reliable [3, 5, 7–10].

As the variable acoustic solutions are gaining popularity in the field of acoustic treatment of spaces, there are few works that study the change in reverberation time values in a room with varying absorption [9, 11, 12]. In most cases, however, only a few different combinations were studied.

The present paper presents measurements of reverberation time in a variable acoustics space with a high level of absorption granularity. It further compares the obtained values with the predictions calculated by several reverberation time models.

The paper is organized as follows. Section 2 presents reverberation time formulas. Section 3 describes measurements in the variable acoustics laboratory. Section 4 presents the results of measurements and reverberation time predictions using the formulas discussed in Section 2. It also discusses the differences between measured and predicted values and reveals, which of the models provides the best results. Section 5 summarizes the work presented in the paper, concludes the findings, and presents ideas for further research.

2. REVERBERATION TIME FORMULAS

Sabine defined reverberation time as the time needed for the sound energy to decrease by 60 dB from its original level after the termination of the excitation signal [4]. Sabine's prediction is given by

$$T_{60} = \frac{0.161V}{S\overline{\alpha} + 4mV}\ , \tag{1}$$

where V is the volume of a space, S is the room surface, 0.161 is an experimentally determined coefficient, $\overline{\alpha}$ is the average absorptivity in a room. $\overline{\alpha}$ is defined as $\overline{\alpha} = \sum_i S_i \alpha_i / S$, where S_i are the areas and α_i is the corresponding absorption of each wall, and m is the attenuation coefficient of the air, the value of which depends on the frequency of sound and the air humidity.

For the Sabine formula to predict the reverberation time of the room accurately, a number of requirements must be met: the energy of sound must be equally diffused throughout the space, which means that the walls are not parallel, there are no big differences between the basic dimensions (length, width, and height), and the absorption is small ($\overline{\alpha} < 0.2$ [5]) and uniformly distributed on all walls [3, 5, 6, 13]. In practice, all of those conditions are almost never met, making the Sabine formula applicable only in a small percentage of rooms [3].

Since the Sabine formula proved useful only in considerably live spaces, Eyring introduced a new reverberation theory based on the mean free path between sound reflections [13]. The mean free path in an enclosed space characterized by a diffuse field is expressed by $\bar{l} = 4V/S$ [14–16]. This leads to the following formula:

$$T_{60} = \frac{0.161V}{-S\ln(1-\overline{\alpha})}\ . \tag{2}$$

The Eyring formula is designed for rooms with considerable absorption [17]. Both Equations (1) and (2) assume that all surfaces have the same average absorption, although in reality, the absorption coefficients of the walls, the floor, and the ceiling can vary greatly. This was addressed by Millington [18] and Sette [19], who introduced the following formula:

$$T_{60} = \frac{0.161V}{-\sum_i S_i \ln(1-\alpha_i)} \; . \tag{3}$$

Another improvement to reverberation time prediction was made by Kuttruff [16]. Similarly to Eyring, he based his model on the mean free path approach. He suggested, however, statistical distribution of sound, introducing a relative variance of the path length $\gamma^2 = (\overline{l^2} - \bar{l}^2)/\bar{l}^2$. Kuttruff's model took into account the shape of the room and distribution of the absorption, as well as corrected the averaging of the sound absorption coefficient, yielding the following equation:

$$T_{60} = \frac{0.161V}{-S\ln(1-\overline{\alpha})\Big(1+\frac{\gamma^2}{2}\ln(1-\overline{\alpha})\Big)} \; . \tag{4}$$

Kuttruff's formula repeatedly gives good reverberation time predictions for rooms, where all walls but one have similar absorption, but not when the absorption is distributed asymmetrically [3].

Although the above formulas present the progress in reverberation time estimation over the years, all of them still assume that the absorption coefficients of the room's surfaces are approximately equal. The first model that included geometrical aspects of the sound field with unevenly distributed absorption was presented by Dariel Fitzroy [20]. His empirically derived equation assumes a relation within three possible decay rates along the three basic axes in a rectangular room and is expressed by

$$T_{60} = \frac{0.161V}{S^2} \sum_j \frac{-S_j}{\ln(1-\alpha_j)} \; , \tag{5}$$

where $j = x, y, z$ denotes the current axis, S_j is the total area of the opposite parallel walls along the axis, and α_j is the average absorption coefficients for each pair of opposite walls. Fitzroy's model is reported to work best for relatively large spaces, such as concert halls [17], but only when they are of rectangular shape [3].

A similar approach was adopted by Arau-Puchades [21], who described the reverberation time of a room to be a geometric weighted average of the reverberation times in three orthogonal directions. The absorption coefficients are determined for each pair of the parallel walls, yielding the following formula:

$$T_{60} = \prod_j \left[\frac{0.161V}{-S\ln(1-\alpha_j) + 4mV}\right]^{\frac{S_j}{S}} \; . \tag{6}$$

A further modification to Fitzroy's formula was proposed by Neubauer [3, 22, 23], who used the fact that both Fitzroy's and Kuttruff's models were based on the concept by Eyring. He introduced a similar correction to Fitzroy's equation as was earlier done by Kuttruff to Eyring's formula. Therefore, Kuttruff's correction was split into two parts – one for the ceiling and floor and another for the remaining walls. Neubauer's formula is expressed by

$$T_{60} = \frac{0.32V}{S^2}\left(\frac{h(l+w)}{\overline{\alpha}^*_{ww}} + \frac{l \cdot w}{\overline{\alpha}^*_{cf}}\right), \tag{7}$$

where h, w, and l are the room dimensions height, width, length in meters, and $\bar{\alpha}^*_{ww}$ and $\bar{\alpha}^*_{cf}$ are the average effective absorption exponents of the walls and the ceiling and the floor, respectively:

$$\overline{\alpha}^*_{ww} = \beta + \left[\frac{\sum_i \rho_{wi}(\rho_{wi} - \overline{\rho}_{ww})S^2_{wi}}{\overline{\rho}_{ww}\sum_i S_{wi}}\right], \tag{8}$$

$$\overline{\alpha}^*_{cf} = \beta + \left[\frac{\rho_c(\rho_c - \overline{\rho}_{cf})S^2_c + \rho_f(\rho_f - \overline{\rho}_{cf})S^2_f}{\overline{\rho}_{cf}(S_c + S_f)}\right], \tag{9}$$

where $\rho = 1 - \alpha$ is the reflection coefficient and $\beta = -\ln(1/\overline{\rho})$.

3. ACOUSTIC MEASUREMENTS

This section discusses the measurements conducted and equipment used during this study in the variable acoustics laboratory *Arni* at the Acoustics Lab of Aalto University, Espoo, Finland. Examples of measured impulse responses are available online [1] .

3.1 Variable acoustic space

The *Arni* room is of rectangular shape, with dimensions 8.9 m × 6.3 m × 3.6 m (length, width, and height). The walls and the ceiling of the room are covered with variable acoustics panels made from painted metal and filled with absorptive material. On the front of the panels, rectangular slots are cut out from the surface. The slots can be opened, letting the sound reach the absorptive material inside, or closed, making the surface reflective. The dimensions of a single panel are 0.6 m × 0.4 m × 2.4 m (length, width, and height). There is a total of 55 panels in the variable acoustics laboratory including 8 on three of the walls, 11 on the fourth wall, and 20 on the ceiling.

3.2 Measurement setup

During the measurements, two Genelec 8030A loudspeakers were used as sound sources. Five G.R.A.S. 1/2-inch free-field microphones of type 46AF served as receivers. The positions of sound sources and receivers are marked in Fig. 1. Moreover, G.R.A.S. power model of type 12AG was used as an amplifier. All equipment was connected to an HP ZBook laptop via MOTU UltraLite mk3 Audio Interface.

The measurement signal was a 3-second long exponential sine sweep. It was played three times for each panel configuration through each sound source, resulting in 6 recordings for each microphone, making a total of 30 test signals recorded for each panel configuration. All in all, 56 panel

[1] `http://research.spa.aalto.fi/publications/papers/smc20-RTmodels/`

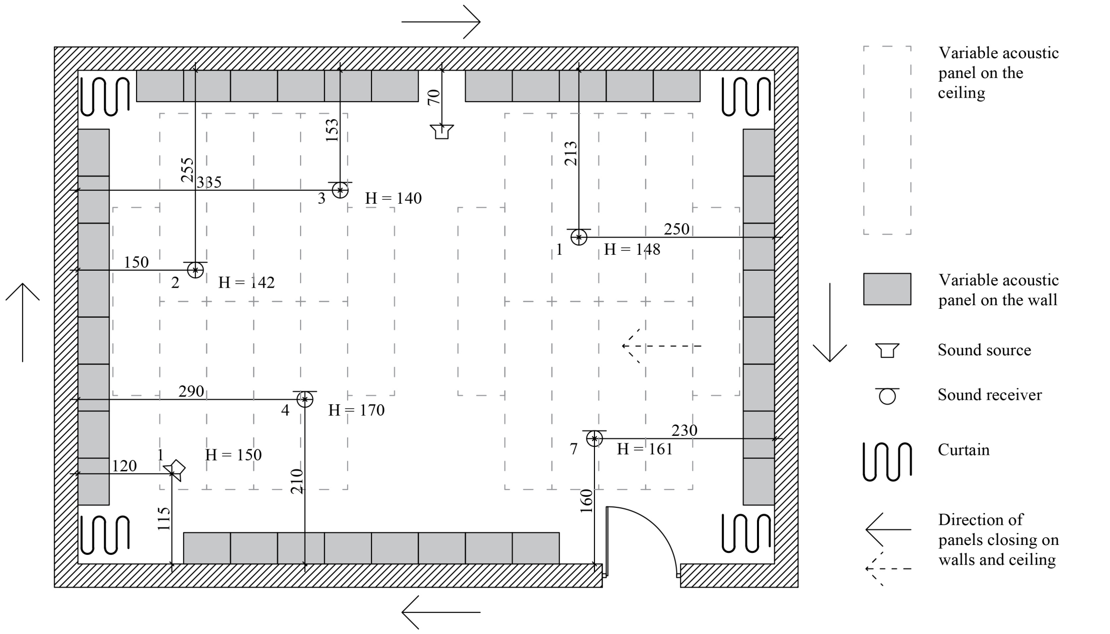


Figure 1: Layout of the variable acoustics laboratory Arni showing the panels and the sound sources and receiver locations. The arrows show the order of panels closing on the walls and the ceiling.

Material	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Panel open [26]	0.86	0.77	0.66	0.45	0.38	0.42
Panel closed [26]	0.09	0.05	0.05	0.04	0.02	0.03
Wall [27]	0.02	0.03	0.03	0.04	0.05	0.05
Floor [27]	0.02	0.03	0.03	0.03	0.02	0.03
Curtain [28]	0.45	0.95	0.99	0.99	0.99	0.99

Table 1: Sound absorption coefficients of materials used as the basis for determining the α in T_{60} calculations.

configurations were measured, the first one having all panels open (conf. no. 1). In the following configurations the panels were being closed one by one (conf. no. 2 = 1 panel closed, conf. no. 3 = 2 panels closed, and so on). Additional 20 configurations were measured by closing only the panels on the ceiling, while the ones on the four remaining walls were open. After the acoustic measurements, the reverberation time was estimated for each configuration according to [24], using the functions included in the IoSR Matlab Toolbox [25].

3.3 Measurement accuracy

The T_{60} were averaged for each configuration according to

$$\overline{T}_{60,n}(k) = \frac{1}{M}\sum_{m=1}^{M} T_{60,m,n}(k), \tag{10}$$

where $M = 30$ is the number of values obtained for one panel configuration (30 = 5 positions $\times$ 2 sources $\times$ 3 sweeps), k is the frequency index, and n is the configuration number. The standard deviations were obtained using the equation:

$$\sigma_n(k) = \sqrt{\frac{\sum_{m=1}^{M}(T_{60,m,n}(k) - \overline{T}_{60,n}(k))^2}{M-1}}. \tag{11}$$

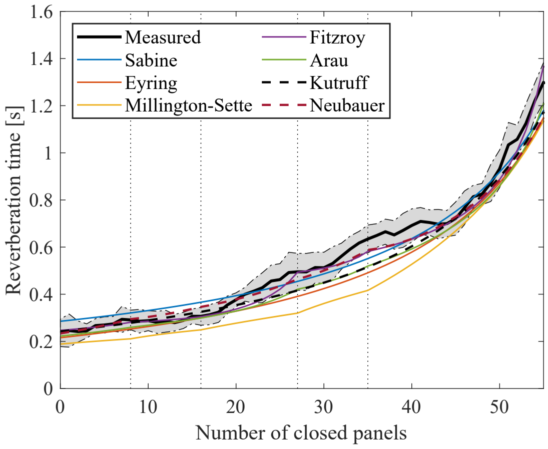
4. COMPARING MEASURED AND MODELED T60

The measured values of the reverberation time were compared with the results of calculations of T_{60} using the formulas presented in Sec. 2. Two scenarios were tested: in the first one, all panels were closing following the direction showed by the arrow in Fig. 1. In the second one, only the panels on the ceiling were closing, whilst the panels on the remaining four walls stayed open. The absorption coefficients of materials used for the calculations are presented in Table 1.

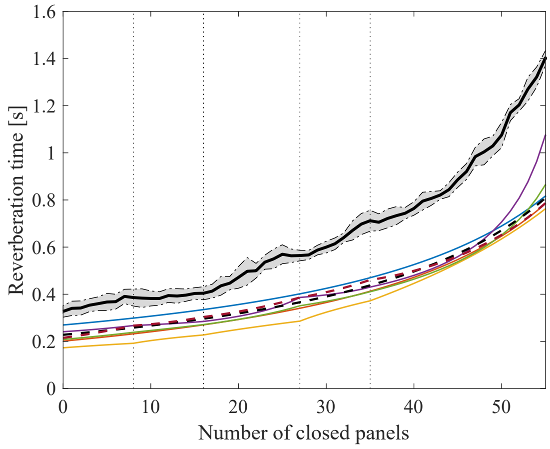
4.1 All panels open to all closed

The measured and modeled values for six octave frequency bands for the case of all panels closing are shown in Fig. 2.

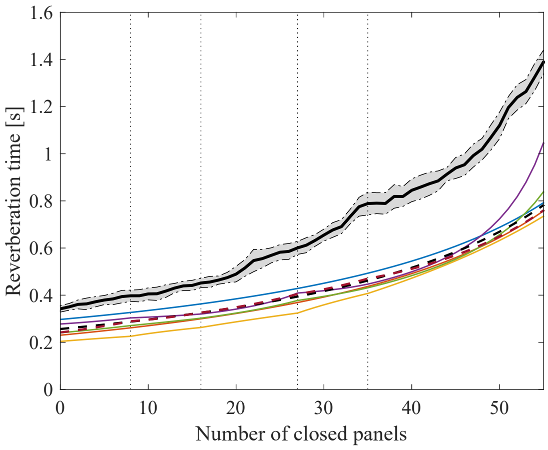
Figure 2a shows that the modeled values fit the measured ones well for 250 Hz. For 500 Hz–1 kHz frequency bands, depicted in Fig. 2b–2d, the predictions underestimate the measured reverberation times. For 4 kHz, presented in Fig. 2e, the predicted values are lower than the measured ones for all formulas except for Fitzroy's, which provides accurate results for the last two combinations. For 8 kHz depicted in Fig. 2f, all formulas give too low RT values when most of the panels are open. When the number of



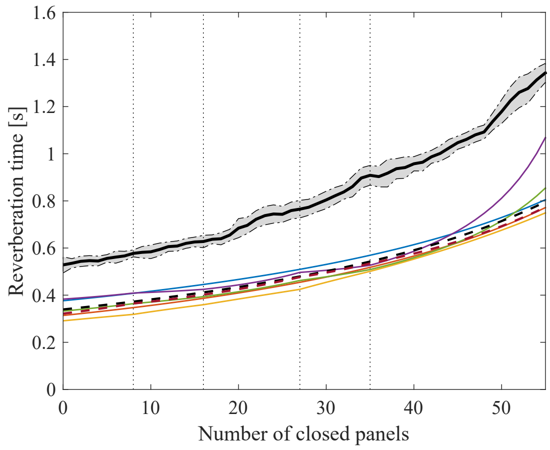
(a) 250 Hz



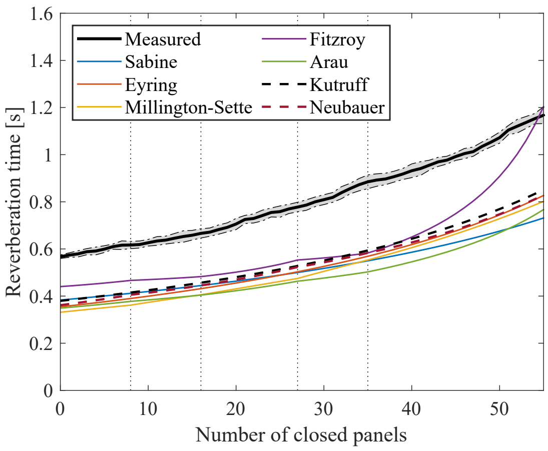
(b) 500 Hz



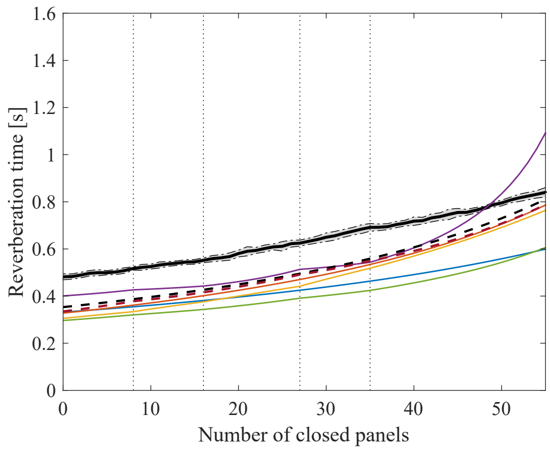
(c) Reverberation time values for 1 kHz



(d) 2 kHz



(e) 4 kHz



(f) 8 kHz

Figure 2: Results of reverberation time measurements and predictions at different octave bands for the case of all panels closing one by one. The shaded area above and below the measured values represents one standard deviation from the mean. The dotted vertical lines mark the end of each wall.

Configuration		Sabine	Eyring	Millington-Sette	Fitzroy	Arau	Kuttruff	Neubauer
All panels open	μ	23.55	27.35	34.41	**17.94**	26.78	22.94	25.13
[%]	σ	**7.32**	15.67	13.88	8.58	16.13	12.93	15.39
All panels closed	μ	31.22	30.31	29.06	**18.81**	28.51	26.38	27.74
[%]	σ	13.04	16.74	17.09	**10.38**	12.49	16.54	16.63
All combinations	μ	27.33	28.47	32.46	**24.34**	33.58	25.90	26.94
[%]	σ	**9.64**	12.89	13.95	11.55	12.90	11.48	11.74

Table 2: Average difference μ and standard deviation σ from the measured T_{60} values for all panels open, all panels closed, and from all panel combinations. The smallest result on each row is highlighted.

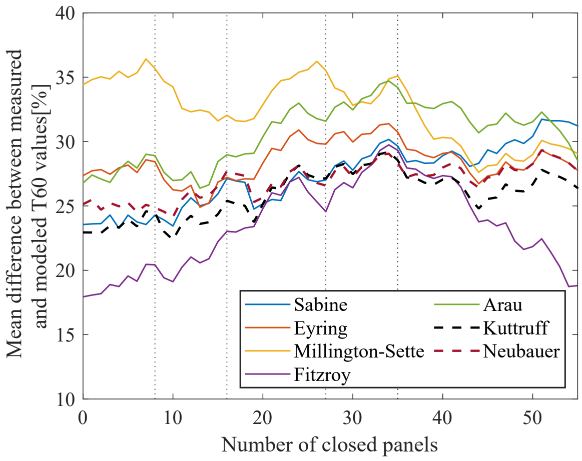


Figure 3: The mean difference between the measured and modeled reverberation time values for the scenario of all panels in the room closing. The dotted vertical lines mark the end of each wall.

closed panels grows, however, the accuracy of Eyring's, Millington-Sette's, Kuttruff, and Neubauer's models increases, whilst Fitzroy's quickly goes from producing too low to too high T_{60} values.

The difference between the measured and modeled reverberation time values was averaged over all frequency bands and presented in Fig. 3. None of the used formulas predict the T_{60} of the room with less than 17% error. The smallest differences were obtained by using Fitzroy's formula.

Additionally, the averaged difference for maximum absorption (all panels open), minimum absorption (all panels closed) and the average difference over all combinations were calculated according to:

$$\mu = \frac{1}{N}\frac{1}{K}\sum_{n=1}^{N}\sum_{n=1}^{K}\Delta\widetilde{T}_{60,n}(k), \tag{12}$$

where $\Delta\widetilde{T}_{60,n}(k) = |\widetilde{T}/\widetilde{T}_{60,n}(k) - 1| \cdot 100\%$, T is the RT predicted with a particular model, and N is the number of configurations over which the difference is averaged ($N = 1$ for cases of all panels open and all panels closed, whilst for all combinations $N = 56$).

The standard deviation was obtained using the formula:

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N}\sum_{k=1}^{K}(\Delta\widetilde{T}_{60,n}(k) - \mu)^2}{NK - 1}}. \tag{13}$$

The averaged differences and standard deviations are shown in Table 2. The results confirm that Fitzroy's formula provides the best predictions, by giving the smallest difference between measured and modeled values. Sabine's formula has the least variation in the predicted RT.

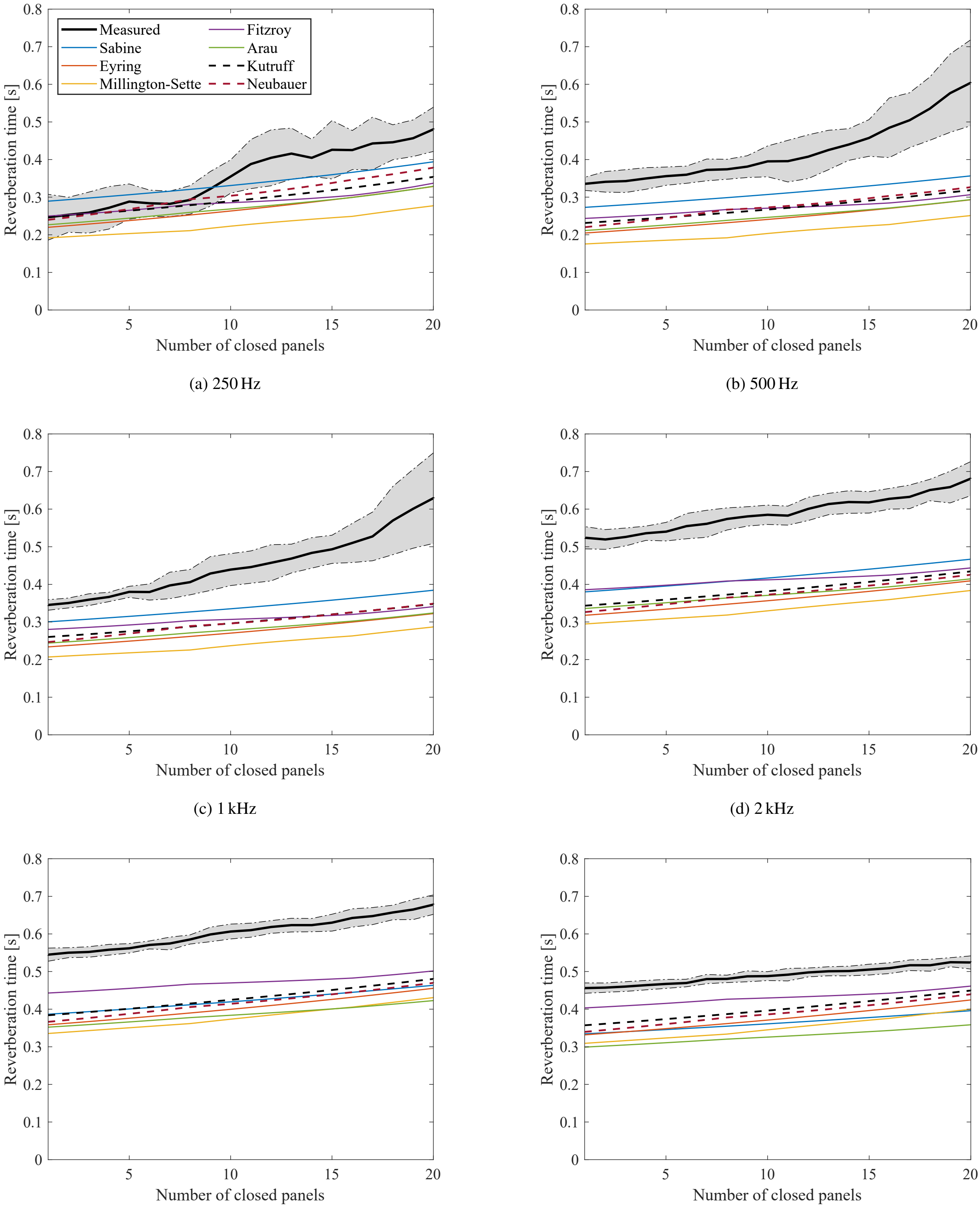
4.2 Panels on the ceiling closing

Figure 4 presents the comparison between the measured and modeled RT values for the scenario when only the panels on the ceiling are closing, whilst the ones on the four remaining walls stay in the open configuration.

The models predict the RT values similar to the measured ones only for the first ten panels closed for 250 Hz presented in Fig. 4a. For all the remaining frequency bands, depicted in Fig. 4b–4d, the T_{60} is underestimated by all the formulas. None of the models mimic the increase in the measured RT values that starts around 10th panel and is the most prominent for 250 Hz in Fig. 4a and visible for 500 Hz and 1 kHz in Fig. 4b and Fig. 4c, respectively.

The differences between the measured and predicted RT values for the case of the ceiling closing is shown in Fig. 5. The predicted values are different from the measured ones by at least 16%. Similarly as in the scenario when all panels in the room were closing, Fitzroy's model provides the smallest error. However, when the absorption decreases, as more panels are closed, Sabine's formula gives very similar results to Fitzroy's.

The averaged differences between measured and calculated RT values were calculated using Eq. (12) ($N = 1$ for all panels open and all panels closed, whilst $N = 20$ for all combinations) and are presented together with their standard deviations obtained with Eq. (13) in Table 3 for the cases of all the panels on the ceiling open, all the panels on the ceiling closed, and all combinations. Fitzroy's formula gives the smallest error when the absorption in the room is high, but Sabine's equation performs similarly when the absorption is low. Moreover, for the case of all panels on the ceiling closed, Sabine's, Fitzroy's Kuttruff's, and Neubauer's models perform very similarly, which is depicted in Fig. 5 when the number of closed panels approaches 20 and in Table 3, where the means of the above



(a) 250 Hz (b) 500 Hz

(c) 1 kHz (d) 2 kHz

(e) 4 kHz (f) 8 kHz

Figure 4: Results of reverberation time measurements and predictions for the case of panels on the ceiling closing one by one, whilst the rest remaining open. The shaded area above and below the measured values represents one standard deviation from the mean.

Configuration		Sabine	Eyring	Millington-Sette	Fitzroy	Arau	Kuttruff	Neubauer
All panels open	μ	22.49	26.49	33.02	**16.74**	26.50	21.83	24.52
[%]	σ	**6.13**	14.35	14.23	9.09	13.72	12.20	13.17
All panels closed	μ	**27.96**	32.52	39.12	28.57	34.86	28.50	29.01
[%]	σ	**11.07**	16.69	15.64	17.03	15.49	16.32	14.79
All combinations	μ	24.52	29.25	35.05	**22.58**	30.33	25.47	26.45
[%]	σ	**7.08**	12.23	14.45	10.76	11.73	10.09	10.00

Table 3: Average difference μ and standard deviation σ from the measured T_{60} values for all panels open, all panels closed, and all panel combinations for the case of only the panels on the ceiling closing. The best result on each row is highlighted.

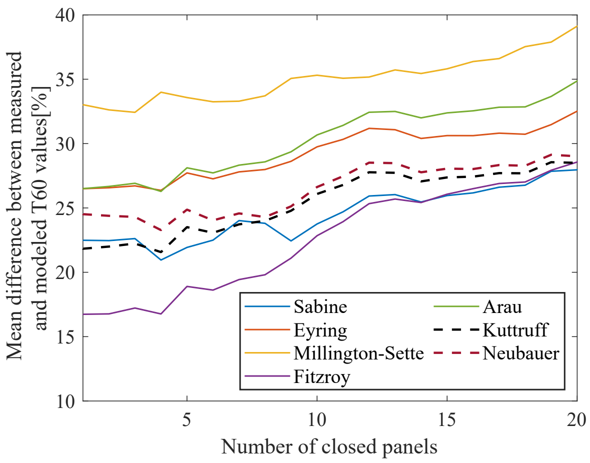


Figure 5: The mean difference between the measured and modeled reverberation time values for the scenario when only the panels on the ceiling are closing.

formulas for the "All panels closed" case differ by 1.05 percentage point or less.

4.3 Error Propagation of Absorption Coefficients

Incorrectly specified absorption coefficients are a common source of error in RT predictions. To check whether the results presented in the study are reliable, we added noise to the absorption coefficient values of the floor, walls and curtains and calculated the RT for all the configurations and models. The simulation was repeated 1000 times and the mean and standard deviations of all the trials were calculated. The experiment showed that even considerable changes in the absorption coefficients (up to 50% of the initial values) did not change the fact that all the formulas underestimated the RT and that the predictions made with the Fitzroy's model were the most accurate.

5. CONCLUSIONS

The study compares seven reverberation time models, which were introduced over the past decades, and discusses their applications. It compares the RT estimations obtained with the models with the results of measurements conducted in the variable acoustics laboratory. The comparison was conducted for two scenarios. In the first one, the absorption in the room was decreased by changing the configuration of acoustic panels from open to closed on four walls and the ceiling. In the second one, only the panels on the ceiling were being closed, whilst the rest remained open.

The results show that all the formulas produce inaccurate T_{60} predictions, with the difference between measured and modeled values above 16% in every configuration. Fitzroy's model performed best in both scenarios, which is a reasonable result due to the fact that it was developed for rectangular rooms with non-uniformly distributed absorption. It also attempts at producing bumps in the estimated RT at the beginning and the end of each wall, which in measured values are especially visible in low frequencies.

Neubauer's and Arau's models, however, were also introduced with assumptions similar to Fitzroy's, but the estimated RT values are far from the measured ones, especially when the absorption in the room decreases. This is especially surprising since the intuition is that both of those models should perform well in situations when the reverberation time along one axis is different from the remaining two (e.g. in the second scenario).

Kuttruff's formula is the second best one for the first scenario (all panels closing). Its average error is large, but stable across all combinations. However, in most cases, it does not follow the increase of the reverberation time, which is visible in the first scenario after 20 panels are closed, and in the second scenario after 10 panels are closed. The poor performance of that formula may be due to the fact that in most of the combinations, the absorption in the room is asymmetric. However, in the cases when it is symmetric or close to symmetric, Kuttruff's model still produces a considerable error.

The fact that Sabine's formula performs so well is surprising, especially taking into account that the smallest error is produced when the absorption is high, and it grows considerably with the decrease of the absorption. Another unexpected result is Eyring's formula returning higher errors than Sabine's model in most cases since it should estimate the T_{60} better in rooms with considerable absorption. The large difference between the predictions made with both of those models and measured RT values may be due to the fact that the formulas require the sound field in the room to be thoroughly diffuse, which is not achieved with any of the panel combinations.

All in all, the error obtained with the discussed models shows that there is a strong need for a more accurate and flexible way to predict the reverberation time. This should be a focus of future research in room acoustics. Additionally, more measurements with the same amount of absorption distributed differently in a room need to be conducted, since the situation in which the absorption changes linearly along the surfaces of the room is unlikely in real life.

Acknowledgments

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