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Correction of the Sabine Formula Using an Artificial Neural Network – A One-Solution Approach

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Abstract
The first part of this paper presents the classical Sabine formula used for estimating the reverberation time (T_{60}) of a room. An experiment was then conducted in which the reverberation time was evaluated using both the Sabine formula and the Schroeder algorithm, the latter estimating T_{60}through the analysis of the Room Impulse Response (RIR).The second part of the paper introduces a corrected Sabine formula obtained by multiplying the original Sabine expression with a correction coefficient $k_{Sab}(\beta,\gamma,\delta)$. The parameters β, γ, and δ were computed using an Artificial Neural Network (ANN). The network was trained on the dataset D_{train}, which consisted of $N = 25401$ RIRs. The corrected Sabine formula was tested on $M = 36288$ RIRs. The mean absolute error ($\overline{e_{Sab}}$) and the mean squared error (MSE_{Sab}) were used as the evaluation metrics for reverberation time estimation. The experimental results are presented using graphs and a table. A detailed comparative analysis shows that the corrected Sabine formula improves the accuracy of the reverberation time estimation by 20.0733% compared to the classical Sabine formula.
Keywords: *reverberation time; Sabine; Eyring; decay curve*

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I. Introduction

A significant scientific contribution to architectural acoustics was made by the American physicist Wallace Clement Sabine. As a result of his systematic experimental investigations, Sabine established a relationship between the room volume, the absorptive characteristics of walls, floors, and ceilings, and the decay of acoustic energy, which he published in the form of a formula in 1922 [1]. In honor of its author, the proposed formula is referred to as the Sabine formula.The Sabine formula calculates the reverberation time T, defined as the time required for the acoustic energy to decay by a factor of 10^6, or equivalently to a level of-60 dB, denoted as T_{60}. Prior to the formulation of the Sabine equation, architectural acoustics relied on empirical experience and intuitive estimates. With the introduction of the Sabine formula as a primary design tool, architectural acoustics became an engineering-scientific discipline. Its application enabled the design of spaces with well-defined acoustic requirements, which is particularly important for concert halls, theaters, amphitheaters, libraries, recording studios, and similar environments.The Sabine formula provides valid results for perfectly diffuse sound fields, where acoustic energy is uniformly distributed in all directions. The assumption of a diffuse acoustic field is fulfilled in rooms with simple geometries and walls with high absorption characteristics. However, in practice, rooms often have complex geometries and non-uniformly distributed absorptive surfaces. Furthermore, the basic Sabine formula assumes a linear dependence of T_{60}on the room surface absorption coefficient α. Consequently, the Sabine formula can lead to significant errors in reverberation time estimation.An improvement of the Sabine formula, or the acoustic model, is the Eyring formula, published in 1930 [2]. The Eyring formula introduces a logarithmic relationship between absorption and reverberation time, increasing the accuracy of T_{60}estimation in rooms with highly absorptive reflecting surfaces. In 1932, Millington proposed a formula that further improves upon the Sabine formula by computing the contribution of each absorptive surface individually [3]. The Fitzroy formula, published in 1959, represents an additional advancement of the Sabine formula and Eyring formula, suitable for rooms with anisotropy, i.e., non-uniformly distributed absorptive surfaces [4, 5]. In this approach, separate reverberation times are calculated along the principal axes ($Tx_{60}, Ty_{60}, Tz_{60}$) and the total reverberation time is derived as the sum of their reciprocal values.Further improvements were introduced in 1988 with the Arau-Puchades formula [6]. This paper presents a new acoustic model for estimating reverberation time under the assumption that acoustic energy decay in a room follows a hyperbolic process. A revision of the Arau-Puchades formula for non-diffuse sound fields is presented in [7]. A simplified methodology for T_{60} estimation using the Sabine formula in mediumsized rooms with non-uniformly distributed absorption is described in [8]. A new mathematical model based on the Sabine formula is presented in [9].

Modern methods for determining reverberation time, unlike the Sabine formula and its subsequent improvements based on global acoustic parameters of a room, utilize the Room Impulse Response (RIR). In 1965, M. R. Schroeder presented in [10] an algorithm for cumulative backward integration of the RIR. This procedure generates an Energy Decay Curve (EDC), representing the total remaining energy in the room as a function of time. By linearizing the portion of the EDC corresponding to exponential decay, the slope is obtained and then extrapolated to -60 dB. This method allows for highly accurate determination of the reverberation time [11, 12]. Due to its accuracy, this algorithm is employed in most commercial and scientific software packages for acoustic analysis based on measured RIRs, in accordance with the international standard ISO 3382 [13].

In this paper, a corrected Sabine formula is presented. The correction was performed to improve the accuracy of the reverberation time T_{60} estimation. First, the classical Sabine formula is described, and its estimation accuracy for T_{60} is evaluated experimentally. The experiment was conducted as follows. A test signal database $\mathcal{D} = \{\mathbf{RIR}_i\}_{i=1}^{N}$ was created, containing $N = 35288$ RIRs, which were generated for rooms with volumes in the range $27 \leq V \leq 500\text{m}^3$ and reflection coefficients $0.1 \leq R \leq 0.9$, using the “Room Impulse Response Generator” software [14].This database was used to assess the accuracy of T_{60} estimation for all N rooms using two methods: (a) the Schroeder integral curve algorithm [10] and (b) the Sabine formula [1].In this experiment, T_{60} obtained from the Schroeder algorithm were considered as reference. The mean absolute error ($\overline{e_{Sab}}$) and mean squared error (MSE_{Sab}) were employed as evaluation metrics. The results are presented both graphically and in tabular form.To further improve estimation accuracy, the Sabine formula was corrected by introducing a correction coefficient $k_{Sab}(\beta, \gamma, \delta)$, whose parameters β, γ, δ were determined using an artificial neural network (ANN). The database $\mathcal{D}$ was split into a training set $\mathcal{D}_{train}$ (70%, 25401 RIRs) and a test set $\mathcal{D}_{test}$ (30%, 10887 RIRs). Subsequently, experiments were conducted to estimate T_{60} for rooms and RIRs from $\mathcal{D}$, $\mathcal{D}_{train}$, and $\mathcal{D}_{test}$ using: (a) the Schroeder algorithm, (b) the classical Sabine formula, and (c) the corrected Sabine formula. A detailed comparative analysis was then performed based on the mean absolute error e and mean squared error MSE, allowing the improvement in accuracy of the corrected Sabine formula relative to the classical Sabine formula to be quantified.

The remainder of the paper is organized as follows. Section II presents the Sabine formula and the experimental results. Section III introduces the corrected Sabine formula. Section IV describes the experiment, presents the results, and provides a comparative analysis. Finally, Section V concludes the paper.

II. Estimation Of The Reverberation Time Using The Sabine Formula

2.1 The Sabine Formula

The change in sound energy density in a diffuse sound field is described by a linear differential equation [16]:

$$\frac{dE(t)}{dt} = -\frac{c \cdot A}{4V} \cdot E(t), \quad (1)$$

where E is the sound energy density, c is the speed of sound, V is the room volume, and $A = \sum_i S_i \cdot \alpha_i$ is the equivalent absorption area. The solution of this differential equation is:

$$E(t) = E(0) \cdot e^{-\frac{cA}{4V}t}, \quad (2)$$

where $E(0)$ is the initial energy density immediately after the acoustic source has stopped. Equation (2) indicates an exponential decay of sound energy [17] in a diffuse field. The reverberation time T_{60} is defined as the time required for the energy to decay by 60 dB relative to the energy level at the moment the acoustic source stops emitting, i.e., $E(T_{60}) = E(0) \cdot 10^{-6}$. Substituting this into (2) yields:

$$e^{-\frac{cA}{4V}T_{60}} = 10^{-6}. \quad (3)$$

By solving (3), the reverberation time is determined:

$$T_{60} = \frac{24 \cdot V \cdot \ln(10)}{cA} \cong \frac{55.26}{c} \cdot \frac{V}{A}. \quad (4)$$

For an air temperature of $t = 20^{o}C$, the speed of sound is $c \cong 343$ m/s, so the final expression for the Sabine formula is:

$$T_{60} \cong 0.161\frac{V}{A} = 0.161\frac{V}{\sum_i S_i \cdot \alpha_i}, \quad (5)$$

where $V[m^3]$ is the room volume, $\sum_i S_i \cdot \alpha_i$ (in sabins) is the equivalent absorption area, $S_i[m^2]$ is the area of the i-th surface, and α_i is the absorption coefficient of the i-th surface.

The results obtained using the Sabine formula were validated experimentally.

2.2 The experiment

To evaluate the accuracy of reverberation time estimation using the Sabine formula, the experiment was conducted as follows. First, a database $\mathcal{D}$ was created, defined as $\mathcal{D} = \{\mathrm{RIR_i}\}_{i=1}^{N}$, containing $\mathrm{N} = 35288$RIRs. The RIRs were generated using the "Room Impulse Response Generator," implemented in the programming language C [14], based on the theoretical framework from [15]. RIRs were generated for rooms with varying volumes ($27 \leq \mathrm{V} \leq 500\ \mathrm{m}^3$) and surface reflection coefficients (walls, floors, ceilings) in the range $0.1 \leq \mathrm{R} \leq 0.9$. Subsequently, the reverberation times $\mathrm{T_{60}}$ were calculated using two methods: (a) the Schroeder integral curve algorithm [10], implemented in Matlab [18], and (b) the Sabine formula [1]. The $\mathrm{T_{60}}$ obtained using the Schroeder algorithm were considered as reference for the subsequent analysis. Finally, for each room, the estimation error $\mathrm{e_{RT_{60}}}$and the overall mean squared error (MSE) were computed. The algorithm according to which the experiment was performed is summarized in the following steps:

Input:$W_{min}, \Delta W, W_{max}, H_{max}$ - room dimensions; $R_{min}, \Delta R, R_{max}$ – surface reflection coefficients; T_h – RIR duration; f_s– sampling frequency.
Output:MSE_{Sab}

FOR $x_w = W_{min} : \Delta W : W_{max}$
FOR $y_w = W_{min} : \Delta W : W_{max}$
FOR $z_w = W_{min} : \Delta W : H_{max}$
FOR $R_{l,r} = R_{min} : \Delta R : R_{max}$
FOR $R_{f,b} = R_{min} : \Delta R : R_{max}$
FOR $R_{f,c} = R_{min} : \Delta R : R_{max}$

Step 1: Room dimensions are:
$ROOM = [x_w, y_w, z_w](\mathrm{m}^3)$,
Step 2: Determination of reflection coefficients:
$R = [R_{l,r}, R_{f,b}, R_{f,c}, R_{l,r}, R_{f,b}, R_{f,c}]$,
Step 3: Calculation of absorption coefficients:

$$\alpha = 1 - |R|^2, \qquad (6)$$

Step 4: Position of the loudspeaker (LS):
$LS = [x_w/2\ \ 1\ 1.5](\mathrm{m})$,
Step 5: Position of the microphone (Mic):

$$Mic = [x_w/2\ y_w - 1\ 1.5]\ (m),$$

Step 6: Generation of the RIR [14]:

$$h = rir(ROOM, LS, Mic, R, c, T_h, f_s),$$

Step 7: Estimation of T_{60} using the Schroeder algorithm [18]:

$$T_{60,Sch} = Sch\_alg(h, f_s),$$

Step 8: Estimation of T_{60}using the Sabine formula [1]:

$$T_{60,Sab} = 0.161 \frac{V}{\sum_i S_i \cdot \alpha_i},$$

where$V = x_w \cdot y_w \cdot z_wandA = \sum_i S_i \cdot \alpha_i$.
Step 9: Calculation of estimation errors:

$$e_{Sab} = T_{60,Sch} - T_{60,Sab}, \qquad (7)$$

END $R_{f,c} = R_{min} : \Delta R : R_{max}$
END $R_{f,b} = R_{min} : \Delta R : R_{max}$
END $R_{l,r} = R_{min} : \Delta R : R_{max}$
END $z_w = W_{min} : \Delta W : H_{max}$
END $y_w = W_{min} : \Delta W : W_{max}$
END $x_w = W_{min} : \Delta W : W_{max}$

Step 10: Estimation mean absolute error:

$$\bar{e}_{Sab} = \frac{1}{N} \sum_{i=1}^{N} |e_{i,Sab}|, \qquad (8)$$

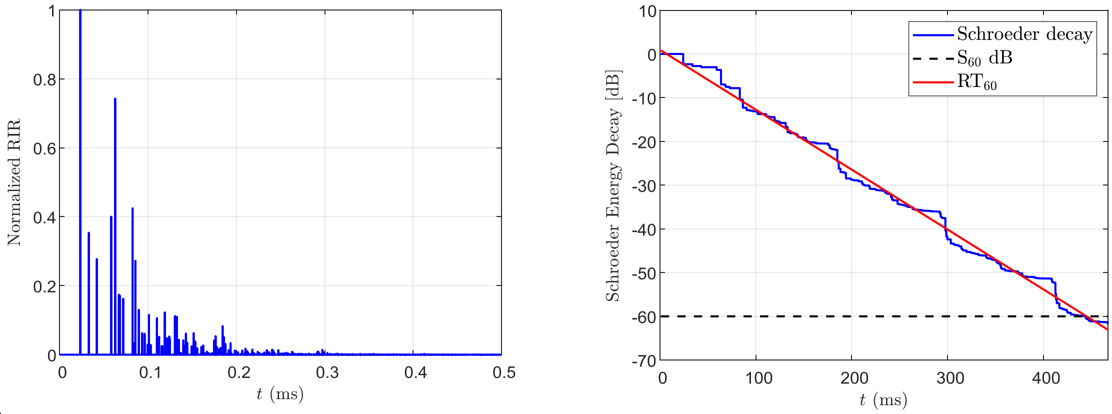
Step 11: Estimation mean squared error:

$$MSE_{Sab} = \frac{1}{N} \sum_{i=1}^{N} e_{i,Sab}^2, \qquad (9)$$

The algorithm was implemented with the following parameters: $W_{min} = 3$ m, $\Delta W = 1$ m, $W_{max} = 10$ m, $H_{max} = 5$ m, $R_{min} = 0.1$, $\Delta R = 0.1$, $R_{max} = 0.9$, $c = 343$ m/s, $T_h = 1.5$ s, $f_s = 44.1$ kHz.

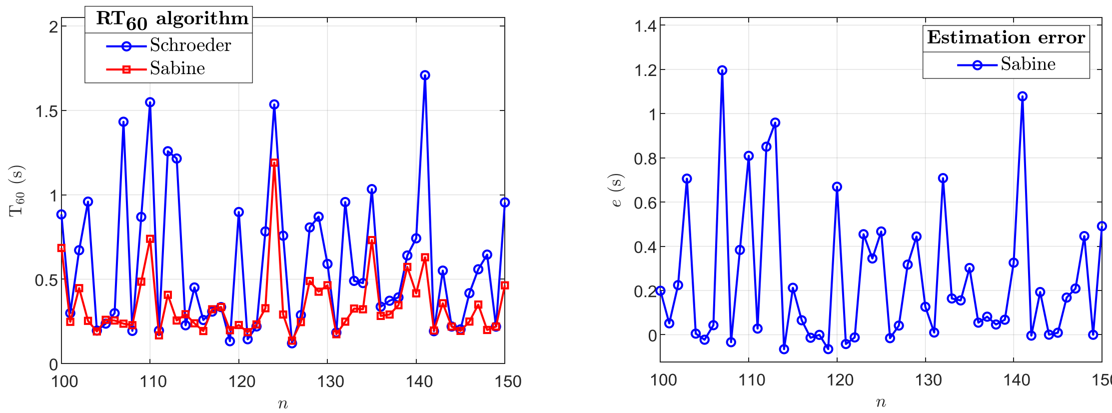
2.3 Results

In Fig. 1(a), the RIR is shown for a room with$V = 10 \times 10 \times 5 = 500$ m3, $R = 0.5$. Fig. 1(b) shows the Schroeder Energy Decay Curve (EDC). In Fig. 2(a), the reverberation times estimated using the Schroeder algorithm and the Sabine formula are presented for rooms with indices $100 \le n \le 150$ from the sequence generated randomly. Fig. 2(b) shows the estimation error e_{Sab} (eq. (7)). The mean absolute estimation error $\bar{e}_{Sab}$ (eq. (8)) and the mean squared error MSE_{Sab} (eq. (9)) are presented in Table I.



a) b)

Figure 1: (a) Normalized RIR, (b) Schroeder energy decay curve (EDC) for a room with $V = 500\ m^3$.



a) b)

Figure 2: (a) Estimated T_{60}using the Schroeder algorithm and the Sabine formula, and (b) the estimation error.

The application of the Sabine formula for estimating T_{60} results in a mean absolute estimation error of $\bar{e}_{Sab} = 0.2180$ s and a mean squared error of $MSE_{Sab} = 0.1157$. To reduce the estimation error, a correction of the Sabine formula was performed.

III. Corrected Sabine Formula

The classical Sabine formula (eq. (5)) was corrected by multiplying it with a correction coefficient $k_{Sab}(V, A)$, i.e.,

$$T_{60,Sab\_corr} = k_{Sab}(V, A) \cdot 0.161\frac{V}{A}. \tag{10}$$

The correction coefficient $k_{Sab}(V, A)$ has the form:

$$k_{Sab}(V, A) = r \cdot e^{\beta V + \gamma A + \delta}, \tag{11}$$

where β, γ, δ are the parameters to be determined. Their calculation was performed using an artificial neural network. The neural network architecture is denoted as $N: \mathbb{R}^2 \to \mathbb{R}, N = [1,1]$ where the input vector is $\boldsymbol{x} = [V, A]^T \in \mathbb{R}^2$ and the output is $y \in \mathbb{R}$. The corresponding weight matrices and bias vectors are$\boldsymbol{W}_1 \in \mathbb{R}^{1\times 2}$, $\boldsymbol{b_1} \in \mathbb{R}$, $\boldsymbol{W}_2 \in \mathbb{R}^{1\times 1}$, $\boldsymbol{b_2} \in \mathbb{R}$. For the development of the ANN, the dataset of rooms and their corresponding RIRs, $\mathcal{D}$, was randomly shuffled and divided into two parts: a) the training dataset $\mathcal{D}_{train}$ (70% → 25401 samples) and (b) the test dataset $\mathcal{D}_{test}$ (30% → 10887 samples). After training the ANN, the coefficients were determined as follows: $\beta = \boldsymbol{W}_2 \cdot \boldsymbol{W}_1(1) = 1.2362 \cdot 10^{-5}, \gamma = \boldsymbol{W}_2 \cdot \boldsymbol{W}_1(2) = -1.6381 \cdot 10^{-5}, \delta = \boldsymbol{W}_2 \cdot \boldsymbol{b}_1 + \boldsymbol{b}_2 = -0.1741$ and $r = 1.8$. By substituting these values into (11), the following is obtained:

$$k_{Sab}(V, A) = 1.8 \cdot e^{1.2362\times10^{-5}\cdot V - 1.6381\times10^{-5}\cdot A - 0.1741}. \tag{12}$$

Finally, the corrected Sabine formula (eq. (10)) is:

$$T_{60,Sab\_corr} = 0.2435 \cdot \frac{e^{1.2362\cdot10^{-5}\cdot V} \cdot V}{e^{-1.6381\cdot10^{-5}\cdot A} \cdot A}. \tag{13}$$

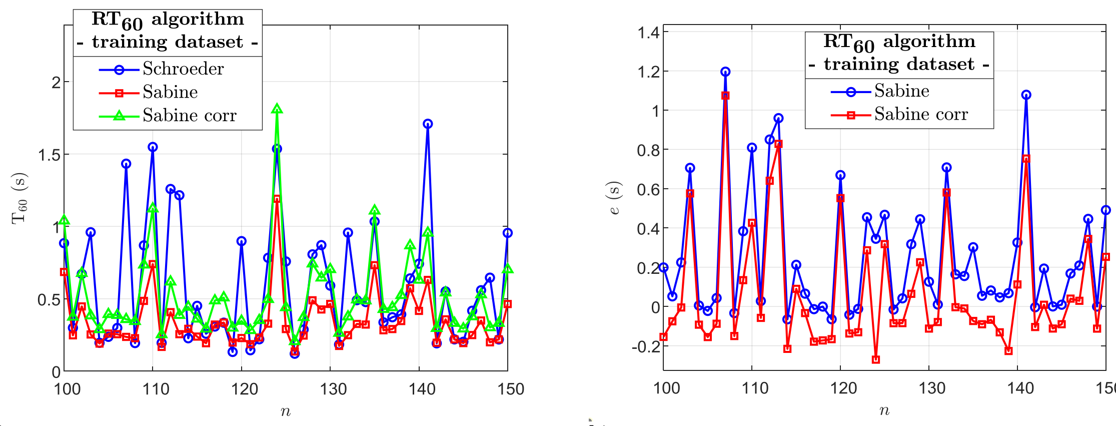
IV. Experimental Results And Analysis

4.1 The Experiment

In order to test the accuracy of the T_{60} estimation using the corrected Sabine formula (eq. (13)), the experiment described in Section 2.2 was repeated. First, the T_{60} values of the RIRs from the training dataset $\mathcal{D}_{train}$ were estimated, followed by the estimation from the test dataset $\mathcal{D}_{test}$. The purpose of estimating the reverberation time for the training dataset, on which the ANN was trained and the coefficients β, γ, δ in k_{Sab} were calculated, was to verify that no overfitting of the ANN occurred.

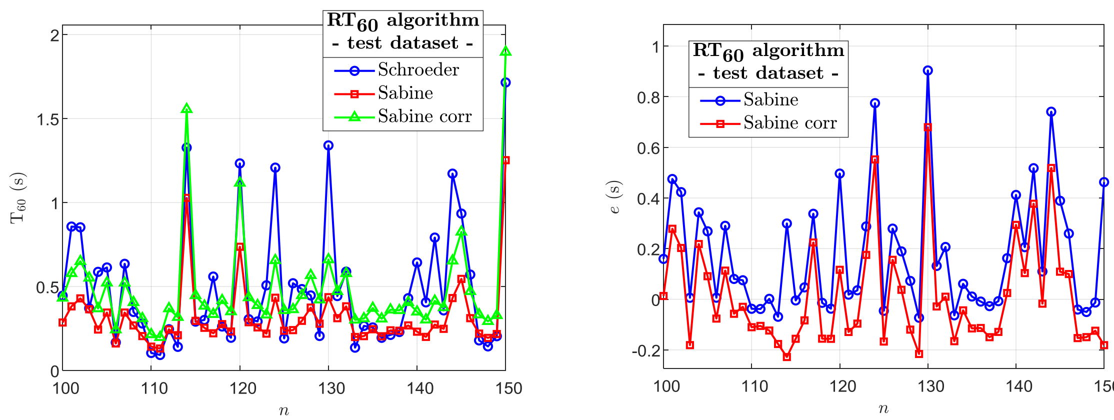
4.2 Results

In Figure 3(a), the reverberation times for the training dataset $\mathcal{D}_{train}$ are shown, estimated using the Schroeder algorithm, the classical Sabine formula, and the corrected Sabine formula, for rooms with indices $100 \leq n \leq 150$ from the $\mathcal{D}_{train}$ sequence. Figure 3(b) shows the estimation errors of the reverberation time using the Sabine formula, e_{Sab}, and the corrected Sabine formula, e_{Sab_corr}. The mean squared errorsare presented in Table I. In Figure 4(a), the reverberation times for the test dataset $\mathcal{D}_{test}$ are shown, estimated using the Schroeder algorithm, the Sabine formula, and the corrected Sabine formula, for rooms with indices $100 \leq n \leq 150$ from the $\mathcal{D}_{test}$ sequence. Figure 4(b) shows the estimation mean absolute errors$\bar{e}_{Sab_train}$ and$\bar{e}_{Sab_test}$ The mean squared errors MSE_{Sab_train} and MSE_{Sab_test} are presented in Table I.



a) b)

Figure 3:Training dataset $\mathcal{D}_{train}$: (a) estimation of T_{60}using the Schroeder algorithm, the classical Sabine formula, and the corrected Sabine formula, (b) estimation errors.



a) b)

Figure 4: Test dataset $\mathcal{D}_{test}$: (a) Estimation of T_{60}using the Schroeder algorithm, the classical Sabine formula, and the corrected Sabine formula, (b) estimation errors.

Table 1: Mean absolute error $\bar{e}_{Sab}$ and mean square error MSE_{Sab}.

RIR base		$\mathcal{D}$		$\mathcal{D}_{train}$		$\mathcal{D}_{test}$	
Estimation errors		$\bar{e}_{Sab}$	MSE_{Sab}	$\bar{e}_{Sab\_train}$	MSE_{Sab_train}	$\bar{e}_{Sab\_test}$	MSE_{Sab_test}
Formula	Sabine	0.2180	0.1157	0.2169	0.1148	0.2207	0.1180
	Sabine_corr	0.1819	0.0691	0.1816	0.0688	0.1825	0.0696

4.2 Analysis of the results

Based on the results presented in Figures 2–4 and in Table I, it can be concluded that, for the estimation of the reverberation time T_{60}, the mean absolute estimation error is:
(a) for the dataset $\mathcal{D}$: $\bar{e}_{Sab} / \bar{e}_{Sab\_corr} = 0.2180/0.1819 = 1.1985$,
(b) for the training dataset $\mathcal{D}_{train}$:$\bar{e}_{Sab\_train} / \bar{e}_{Sab\_train\_corr} = 0.2169/0.1816 = 1.1944$,
(c) for the test dataset $\mathcal{D}_{test}$:$\bar{e}_{Sab_test} / \bar{e}_{Sab_test_corr} = 0.2207/0.1825 = 1.2093$times smaller, respectively.
For the estimation of the reverberation time T_{60}, the mean square estimation error for the rooms and RIRs in the datasets is:
(a) for the dataset $\mathcal{D}$: $MSE_{Sab} / MSE_{Sab\_corr} = 0.1157 / 0.0691 = 1.6744$,
(b) for the training dataset $\mathcal{D}_{train}$: $MSE_{Sab\_train} / MSE_{Sab\_train\_corr} = 0.1148/ 0.0688 = 1.6686$,
(c) for the test dataset $\mathcal{D}_{test}$: $MSE_{Sab_test} / MSE_{Sab_test_corr} = 0.1180/ 0.0696 = 1.6954$times smaller, respectively.

The consistency of the estimation errors for the datasets $\mathcal{D}$, $\mathcal{D}_{train}$, and $\mathcal{D}_{test}$ ($\bar{e}_{Sab} = \{0.1819, 0.1816, 0.1825\}$, $MSE_{Sab} = \{0.0691, 0.0688, 0.1825\}$) indicates that no overfitting occurred during the training of the artificial neural network. The values of the estimation errors $\bar{e}_{Sab}$ and MSE_{Sab} show that the correction of the Sabine formula led to an increase in the accuracy of the T_{60} estimation by $(19.85 + 19.44 + 20.93)/3 = 20.0733$ %.

V. Conclusion

This paper presents a corrected Sabine formula for estimating the reverberation time in a room. The correction was performed by multiplying the classical Sabine formula by the correction coefficient k_{Sab}, whose parameters β, γ, δ were determined using an artificial neural network. The ANN was trained on the dataset of RIRs $\mathcal{D}_{train} = \{RIR_i\}_{i=1}^{25401}$, where the target was the set of RIRs obtained using the Schroeder algorithm. The accuracy of T_{60} estimation using the corrected Sabine formula was then tested on the set $\mathcal{D}_{test} = \{RIR_i\}_{i=1}^{10887}$. A detailed comparative analysis of the estimation accuracy measures, mean absolute error $\bar{e}_{Sab}$ and mean square error MSE_{Sab}, showed that the application of the corrected Sabine formula, compared to the classical Sabine formula, led to an improvement in the estimation accuracy of the reverberation time by 20.0733%.

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