


Article

Experimental Validation of the Model of Reverberation Time Prediction in a Room

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Abstract: It is well known that the uncertainty of input data has a great influence on the accuracy of room acoustics simulations. The aforementioned accuracy is significantly influenced by the selection of the acoustic properties of room-delimiting materials. Moreover, simulation errors are attributed to the fact that rooms can be very irregular and sound diffusion can be uneven, and thus sound absorption can be unevenly distributed over the surfaces. Therefore, a very important element is the validation of the simulation model of interior acoustics, even when we use ready-made software dedicated to interior acoustics for the simulation. In the article, the reverberation room model simulated in the ODEON program was subjected to validation. The program is based on a hybrid method combining the ray and virtual source methods. For the validation, appropriate measurements of the reverberation time in that room were carried out. The validation was undertaken using the criterion of correct validation, consisting of comparing the value of the comparison error and the value of the validation uncertainty.

Keywords: architectural acoustics; reverberation time; reverberation room; ODEON; validation



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1. Introduction

The acoustics of a room depends on the geometry, sound absorption or diffusivity of the acoustic field [1–3]. The acoustic properties of rooms are expressed by many different parameters, whose significance has been recognized by many researchers [4–6]. The most important parameter describing the interior acoustics is the reverberation time, which has a significant impact on other parameters used in this description [7,8]. Modern methods of design and acoustic adaptation of interiors are based on numerical methods [9]. Room acoustics can be simulated in two ways. The first one consists in solving the wave equation with the known solutions for rectangular rooms. For any room geometry, we apply the finite element method (FEM) [10,11], the finite-difference time-domain method (FDTD) [12,13] and the boundary element method (BEM) [14]. In the mid-low frequency range, especially when wave phenomena are strongly visible, wave methods are considered more accurate than geometric methods [15,16]. The BEM frequency domain is based on integral equations. This method is acknowledged because it is a convenient numerical tool for unlimited acoustic problems as its integral equation inherently satisfies the Sommerfeld radiation condition [17]. The fast multipole method (FMM) enables BEM to handle large acoustic models at high frequencies. This allows one to efficiently solve large limited problems, such as those of room acoustics [18]. In addition, FDTD, as a classic simulation method in the time domain, has good potential in a wide range of acoustic applications, including room acoustic simulations [19]. Yet, it is not certain that, given the complexity of the algorithms and numerical uncertainties, wave methods provide the best results. These techniques are expensive in terms of computation, especially in the range of medium and high frequencies, and they require knowledge of boundary surfaces of rooms, which is very often unavailable to the researcher (i.e., complex surface impedance). The second method, based on geometrical acoustics (GA) [20], is adopted for the frequency range

above the Schroeder frequency in the room. The limitation of the GA method involves the fact it can be applied for medium and high frequencies for which the wavelength is small in relation to the dimensions of the room. Despite this, the geometric method is more computationally efficient compared to wave methods. Moreover, the problem of boundary conditions in the geometric method is reduced to the real coefficient of sound absorption by the material of the partitions delimiting the room. There are two main ways to model geometric acoustics: the ray-tracing method [21] and the image-source method [22]. In the simulation of room acoustics, diffuse reflection plays a very important role [23,24]. The modeling of room acoustics is approximated by hybrid approaches or the radiosity technique (the random-walk method) [25]. Various ways of implementing the GA algorithm can be distinguished, taking into account such aspects as: scattering coefficients [24], the choice of a transition point between two computation methods in hybrid algorithms [26] and the technique used to compute the diffuse reflections [27]. As a consequence, different algorithms provide different results when simulating the same room with identical input data [28,29]. The uncertainty of the final results of room acoustics modeling results from the uncertainty of many input parameters of the model, which should be identified and, if possible, reduced [9]. Computer simulations can be performed with ready-made software, e.g., ODEON [30,31]. Such simulation requires a three-dimensional room model that reflects the construction of the wall, floor and ceiling structures. For such a model, both sound absorption and reflection coefficients should be assigned to individual materials. At the design stage of new rooms, it is usually not difficult, because in simulations materials are used whose parameters are known from measurements or catalogs provided by manufacturers. However, at the stage of acoustic adaptation, the problem becomes significant, as most often the exact sound absorption or sound reflection coefficients of the materials present in the room are not known. That is why the validation of the numerical model is so important. In this article, such a validation was performed using laboratory measurements in a reverberation room. A model of such a reverberation room is presented, along with the measurement methodology and a validation method. The choice of this room was deliberate, because the purpose of this article is both to demonstrate the importance of validation and to test the “new” method of validation in interior acoustics. Only in laboratory conditions do we know both the acoustic absorption of the room and the behavior of the acoustic wave under various conditions of air humidity or air temperature.

2. Method

2.1. Measurement of Reverberation Time in a Reverberation Room

The measurements were taken in the reverberation room located in the acoustics laboratory at the Faculty of Civil Engineering of the Silesian University of Technology (Figure 1).

The volume of the reverberation room is 192.7 m³ [32] and its shape meets the requirements of the standard [33]:

$$l_{\max} < 1.9V^{\frac{1}{3}}, \quad (1)$$

where:

l_{\max} —the length of the longest straight line which fits within the boundary of the room (e.g., in a rectangular room it is the major diagonal), in meters,

V —the volume of the room, in cubic meters.

measured sound decay curves. A total of $12 \times 6 = 72$ measurements were made. One of these systems is shown in Figure 2.



Figure 2. Microphone system—the source during the reverberation time of the reverberation room.

According to the standard [33], the positions of the microphones during the measurements were at least 1.5 m apart and at least 2 m from the sound source [34]. The measurements were made by the intermittent noise method. The transmission path consisted of a white and pink noise generator with an amplifier and a loudspeaker with spherical radiation characteristics. The receiving part consisted of an acoustic analyzer, microphones, pre-amplifier, acoustic calibrator and a computer with installed software.

2.2. Modeling

The ODEON software is a platform designed to simulate room acoustics. It applies a hybrid method using the algorithms of the ray method, image source method and energy method. For better understanding, the geometrical methods used in ODEON are presented.

2.2.1. Ray Method

In the ray method, a continuous acoustic wave is assumed to be a discrete set of sound rays that propagate at the speed of sound. These waves are emitted by the source and carry an equal part of the energy that is lost in subsequent reflections. The loss of this energy is proportional to the sound absorption coefficient of the boundary surface. When a wave hits a surface, it is reflected, which means that the new direction of wave propagation follows Snell's law, which is known from geometric optics [35,36]. As the probability of hitting a specific point is close to zero, the receiving point is replaced with spatial elements, e.g., cones [37] or pyramids [38]. The energy drop due to the distance of the receiving point from the sound source is taken into account by the decrease in the number of rays reaching the point as the distance from the source increases. Thus, there is a risk of collecting false reflections and not catching the existing reflections. The ray may also hit the area A representing the receiving point after time t . This happens if the wave front represented by the ray is not larger than $A/2$. For this reason, the minimum number of rays N is estimated as:

$$N \geq \frac{8\pi c^2}{A} t^2, \quad (2)$$

where c is the speed of sound in the room in m/s.

As a result, all energy-related data are averaged in the observation area, leading to the impulse response of the room in the time domain.

2.2.2. The Image Source Method

The image source method is considered to be a good approximation since the wavelength is short compared to the dimensions of the room. This means that it is suitable for simulating large spaces and high frequencies.

In this method, the geometrically determined mirror reflection of the acoustic wave is replaced by the reflection of the real sound source on the reflecting surface. On the extension of the direction of the ray reflected behind this plane, the virtual source is placed. The power of this source is equal to the power of the real source minus the energy losses resulting from the acoustic absorption of the partitions delimiting the room. On each reflecting surface real sources are distributed, which are the first order apparent sources. By mapping multiple reflections from all interior surfaces, higher order sources are generated. For subsequent reflections, the number of possible sources of images is [39]:

$$N_{sources} = 1 + \frac{n}{n-2} \left((n-1)^i - 1 \right) \approx (n-1)^i, \quad (3)$$

where:

n —the number of surfaces delimiting the room,

i —order of reflections of the sound wave.

Figure 3 shows the mirroring process, where S represents the source and I represents the mirror source. \mathbf{N} denotes the normal to the surface, and \mathbf{v} is a vector from the source S to any point that lies on the surface, most commonly at any corner point. Thus, we can write [40]:

$$I = S - 2 \cdot \mathbf{N} \cdot |\mathbf{v}| \cdot \cos \alpha, \quad (4)$$

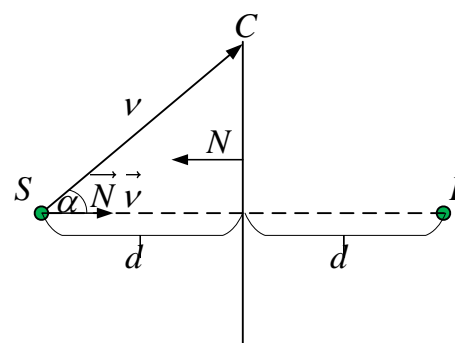


Figure 3. Mirroring process of source S to the surface, creating the imaged source I .

In this method we set the termination condition, which can be set as the maximum order of reflections or maximum distance. Accordingly, the first order IS can be generated by mirroring the source S on all planes of the room. Then, for the second order reflections, all generated IS from the previous step must be mirrored on the surfaces of the room again. This process is repeated until the termination condition is met.

2.2.3. Hybrid Methods

The disadvantages of the ray method and the image source method have led to the development of hybrid models that combine the best features of these two methods [38,41]. The hybrid model uses the visibility test, which consists of tracing the rays from the source and recording the surfaces on which the rays fall. This method allows the elimination of the occurrence of rays representing the same sequences of sound waves reflections from the walls.

2.2.4. Computer Simulation Using ODEON

In the ODEON program, in the calculation algorithm, the “secondary sources” method was applied. After passing from the early reflections, the rays are treated as energy carriers

and not as an element examining the geometry of the room. Each time a ray hits the surface, a secondary source is generated at the hit location. The energy generated in this secondary source is the total energy of the primary source divided by the number of rays and multiplied by the reflection coefficient of the surface on which it previously fell before reaching this secondary source. Each secondary source is a new sound source. Thus, the intensity of the new source is proportional to the cosine of the angle between the normal surface and the vector that starts at the secondary source point and ends at the new reception point. The reflection intensity at the reception point also decreases, in line with the inverse square law, at the beginning of the intensity vector in the starting point, which is the secondary source. Figure 4 shows schematically how the computational model behaves. Two adjacent rays are traced until the fifth reflection. From among all possible directions of reflection, one of them is chosen (randomly according to Lambert's law). The next two reflections are specular and both rays find secondary sources S1 and S12. The rays of these sources generate one reflection. Rindel [39] determined that the optimal number of reflections is between 500 and 1000.

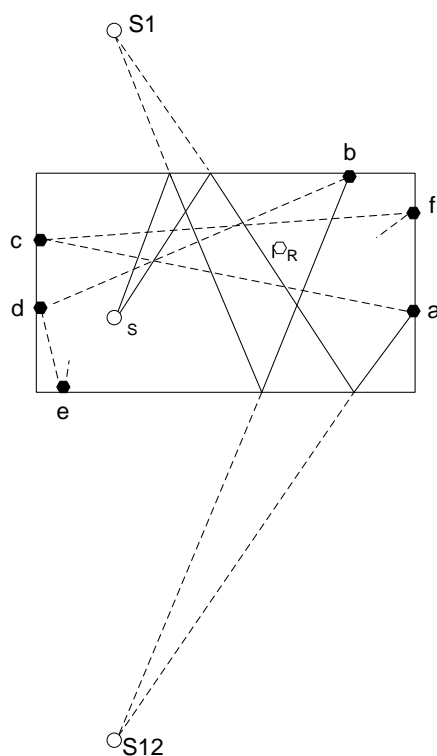


Figure 4. Principle of a hybrid model.

In the ODEON simulations, the scattering method was set to Lambert, and all directions of late reflections were calculated using the scattering coefficients. The sound source and receivers were placed at the same locations as during the measurements.

In the ODEON program, the geometry of the reverberation room and the positions of microphones and the sound source were mapped. The measurements and simulations were performed at a temperature of 15.5 °C and a relative humidity in the room of 30%. At the outset, the acoustic parameters of building partitions were selected, corresponding to a plastered and painted wall.

2.2.5. Validation

The following definition was adopted:

Definition 1. *Through the validation, the correctness of the model was assessed and adopted in relation to the results of the experimental tests.*

In order to validate the model, the method proposed by Stern [42] was adapted. Using Condition (5), the criterion of correct validation was described.

$$|E| < U_V, \quad (5)$$

where:

E —value of comparison error,

U_V —validation uncertainty.

The validation error value was determined as follows:

$$E = \delta_E - \delta_S, \quad (6)$$

where:

δ_E —experimental error,

δ_S —simulation error.

$$\delta_S = \delta_{SMA} + \delta_{SPD} + \delta_{SN}, \quad (7)$$

where:

δ_{SMA} —error resulting from the assumption of the model,

δ_{SPD} —error resulting from the use of input data.

δ_{SN} —error resulting from numerical simulation.

Based on the analysis of Formula (7) and taking into account the succeeding results of Stern et al. [43], it was concluded that the simulation error is very difficult to estimate for ready-made software such as ODEON. Therefore, a simpler method of its calculation has been proposed, expressed by the formula:

$$\delta_S = |S - M|, \quad (8)$$

where:

S —simulation result,

M —measurement result.

The value of validation uncertainty was defined as:

$$U_V^2 = U_E^2 + U_{SPE}^2 + U_S^2, \quad (9)$$

where:

U_E —experimental uncertainty,

U_{SPE} —experimental uncertainty in the use of input data,

U_S —simulation uncertainty.

3. Results and Discussion

The acoustic absorption of the room was corrected in such a way as to ensure the conditions of good validation described by Formula (5).

Finally, the sound absorption coefficients of the walls as presented in Table 1 were adopted and compared with the tabular values for concrete.

Table 1. Adopted sound absorption coefficients of room delimiting partitions (column 2) and sound absorption coefficients of concrete (column 3). Computer simulation and the measurement of reverberation time in the reverberation chamber.

Frequency [Hz]	Adopted Sound Absorption Coefficients	Sound Absorption Coefficients of Concrete
63	0.011	0.01
125	0.016	0.01
250	0.015	0.02
500	0.02	0.02
1000	0.02	0.02
2000	0.026	0.02
4000	0.03	0.05

In the first research step, the δ_S differences were determined using Dependence (8), and the results are presented in Table 2.

Table 2. Computer simulation and reverberation time measurement in the reverberation chamber.

Frequency [Hz]	Measurement [s]	Simulation	Validation Error (8)
63	13.75	13.29	0.46
125	9.08	9.00	0.08
250	9.53	9.26	0.27
500	6.61	6.76	0.15
1000	5.8	5.99	0.19
2000	3.76	3.57	0.19
4000	1.94	1.76	0.18
average 500, 1000, 2000	5.39	5.44	0.05

The mean relative error of the approximation of the reverberation times for the frequencies in the range of 63–4000 Hz is 4%. However, the relative error for the average reverberation time in the frequency range of 500, 1000 and 2000 Hz is 0.9%

The experimental error δ_E was adopted as an estimate of the mean standard deviation of the mean value, in line with the formula:

$$\delta_E = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^n (\bar{T} - T_i)^2}, \quad (10)$$

where:

n —number of measurement samples,

T_i — i -th measurement of reverberation time,

\bar{T} —arithmetic mean of all reverberation time measurements.

The statistical error in Equation (10) decreases with the rise in the number of samples, since under the law of large numbers, it tends to the constant value of the standard deviation of the random variable. The error resulting from the δ_S numerical simulation was accepted as the difference between the measured reverberation time and the simulated time. Without knowing the estimation error of the hybrid method, it would be difficult to estimate this error in a different way. However, taking into account that δ_S adopted in the described manner is the maximum error of the simulation, it should be stated that such an approach will at best overestimate this result. The results of the error values are summarized in Table 3.

Table 3. Validation parameters of the reverberation time T. Value of error.

Frequency [Hz]	Parameters of Error [%]		Value of Error [%]
	δ_E	δ_S	E
63	5.74	3.34	2.4
125	3.01	0.88	2.13
250	1.92	2.83	0.91
500	1.38	2.27	0.89
1000	0.98	3.28	2.3
2000	0.64	5.05	4.41
4000	0.59	9.28	8.69

The experimental uncertainty E_U was adopted as the expanded uncertainty at the confidence level of 95%, which was expressed by the formula:

$$U_E = U_{95}(\bar{T}) = k(n) \cdot \delta_E, \quad (11)$$

where:

$k(n)$ —extension value taking into account the student's t distribution,

\bar{T} —arithmetic mean of all reverberation time measurements.

In the present case $k(n) = 1.96$.

Table 4 shows the uncertainty of the validation.

Table 4. Validation parameters of reverberation time T. Error value.

Frequency [Hz]	Uncertainty of Measurement and Simulation [%]		Uncertainty [%]
	U_E	U_S	U_V
63	11.26	3.34	11.74
125	5.90	0.88	5.96
250	3.76	2.83	4.71
500	2.70	2.27	3.53
1000	1.92	3.28	3.80
2000	1.25	5.05	5.20
4000	1.15	9.28	9.35

As can be seen from Tables 3 and 4, Condition (5) is fulfilled for all frequency bands.

The fulfillment of the condition of good validation is confirmed by the presentation of the measurement and simulation results in one graph, as shown in Figure 5.

We have demonstrated that the condition of good validation has been met, and we confirm this condition graphically in Figure 5. However, we must add that the “proximity” of the measurement and simulation results is not enough to say that the simulation reflects the measurement result. If the measurement and simulation results fluctuated around each other, or if they were a product of randomness, we might not notice it. Therefore, in order to demonstrate, first, the high convergence of the results and, second, the statistical significance of the results, a correlation analysis was performed. The results of the analysis are presented in Figure 6.

As it can be observed, the correlation is at the level of $r = 0.9986$, which indicates a very high convergence of the results, and the test probability $p \ll 0.05$ indicates the statistical significance of the results. Thus, we conclude that the results are not accidental. However, the correlation alone is not enough to claim the similarity of results. The simulation and measurement results are identical when the regression line reflects the equation $y = x$. Therefore, the equation of the line shown in Figure 6 was determined:

$$S = 0.9729M + 0.0754, \quad (12)$$

where:

S —simulation result,

M —measurement result.

As can be seen, the slope of the line is close to one and the shift along the vertical axis is very small.

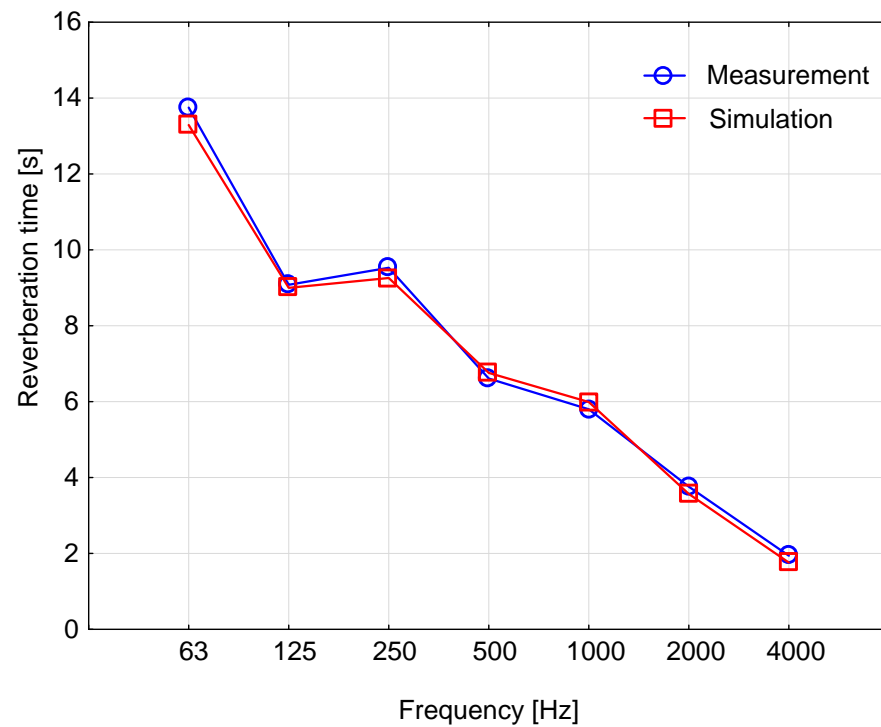


Figure 5. The results of the reverberation room measurement and simulation.

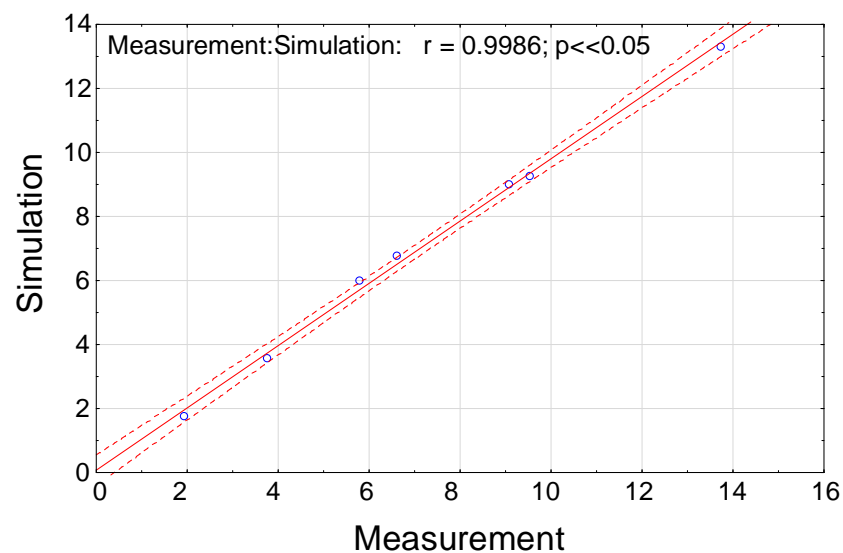


Figure 6. Scatterplot with correlation analysis.

4. Conclusions

The main goal was the demonstration of the validation of a numerical model. It was demonstrated that such a validation is also indispensable when using a ready-made computer program. Such a need arises mainly from the fact that errors occur when assigning certain values of sound absorption or sound diffusion to the partitions delimiting the room.

For the purpose of validation, a method was proposed that consisted of comparing the value of the comparison error with the validation uncertainty. To ensure control over the model, the research was carried out in laboratory conditions in a reverberation room. It was found that the proposed method of validation was successful and it can be successfully used in the modeling of more complex rooms. In addition, the work describes the methods of acoustic geometry, which can be used when analyzing interior acoustics.

The following main conclusions can be drawn from the work:

- the condition of the correct validation of Equation (5) known from the validation of proprietary numerical models works well during the modeling in ready-made software platforms when the input parameters are subject to high uncertainty;
- the simulation error proposed by the authors with Formula (8) can be successfully used to validate numerical models in ready-made computer programs, when the input parameters are subject to high uncertainty;
- the confirmation of the measurement reflected through simulation may be undertaken through regression analysis, where the regression equation $y = x$ is interpreted as a very good (functional) representation.

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