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Research Paper

Frequency-Dependent Comparison of Measured and Sabine-Predicted Reverberation Times in a Concert Hall

Damian Lengacher[1], Lars Arnold Ritter[2]

[1]Independent Researcher, Switzerland; [2]Independent Researcher, Switzerland.

Corresponding Author: Lars Arnold Ritter (l.ritter@unibit.bg)

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ABSTRACT

This study examined how closely the simple Sabine equation predicted the reverberation time of a working concert hall, and how its agreement with in-situ measurements varied across frequency. The hall, a multi-purpose music club of about 665 cubic metres, was surveyed geometrically, and the area and material of every interior surface were recorded. Equivalent absorption areas were derived for the octave bands from 125 to 4000 hertz from published absorption coefficients, and reverberation times were calculated with the Sabine equation. Measurements followed the procedure of the international standard for performance spaces, using an omnidirectional dodecahedron source combined with a subwoofer, a calibrated pressure microphone, and a logarithmic sine sweep. Three source positions and up to nine microphone positions were combined, and the late decay was evaluated and doubled to obtain the reverberation time. The single-number average across the six bands agreed closely, differing by less than two per cent. The band-by-band picture differed sharply. At 125 hertz the measured reverberation fell about 59 per cent below the Sabine value, whereas between 1000 and 2000 hertz it lay roughly two thirds above the calculation; agreement was closest near 250 to 500 hertz. The findings showed that broadband agreement can mask large, opposing frequency-dependent errors, and that measurement remained indispensable when an existing room was to be optimised.

Keywords: reverberation time, room acoustics, Sabine equation, equivalent absorption area, octave-band analysis, concert hall

INTRODUCTION

Room acoustics determines how clearly music and speech are perceived in an enclosed space, and the reverberation time is the parameter most often used to describe it. Reverberation time is the interval over which the sound pressure level in a room falls by 60 decibels after a source is switched off, and it depends on the room volume together with the absorption provided by the bounding surfaces and their materials. The relationship between these quantities was established by Sabine, whose equation tied the reverberation time to the room volume and to the equivalent absorption area.[1] More than a century later the same equation still serves as the starting point for most room-acoustic planning, because it needs only the geometry of a room and tabulated absorption coefficients.[2]

The equivalent absorption area expresses the total sound-absorbing capacity of a room as the sum of each surface multiplied by its frequency-dependent absorption coefficient.[3] The Sabine model assumes a diffuse sound field in which energy spreads evenly and absorption is moderate and uniformly distributed, conditions that real performance spaces rarely satisfy. Since absorption changes strongly with frequency, both the calculation and the measurement have to be carried out band by band. Whether a simple calculation can reproduce what is actually measured in a room has been examined repeatedly, and the relationship between prediction, simulation and measurement remains a recurring question in the field.[4]

Standardised procedures exist so that reverberation measurements can be repeated and compared, the most widely used being the international standard for performance spaces.[5] The present work applied that procedure to an existing concert hall and set the result against a Sabine calculation based on a detailed surface survey. The aim was to quantify, for every octave band between 125 and 4000 hertz, how far the calculated reverberation time departed from the measured value, and to identify the room features that drove the largest deviations. A multi-purpose music club was selected because its hard plastered walls, parallel geometry and raised spectator podium make it both acoustically demanding and typical of venues whose owners often wish to improve them.

MATERIALS & METHODS

The investigated room was the concert hall of the Moshpit Music-Club in Naters, Switzerland, a multi-purpose venue with a capacity of about 500 people that combines a standing parquet area, a bar near the south wall, a stage in one corner and a raised spectator podium in the opposite corner. In plan the hall measured roughly 11.6 metres by 13.6 metres. Its ceiling was inclined by 8.4 degrees, so a mean height of 4.85 metres was taken from the highest and lowest points. Multiplying the plan area by this height gave a gross volume of about 768 cubic metres, and after the stage, bar, podium and sanitary rooms were subtracted the net air volume used in the calculation was 664.75 cubic metres. Walls consisted mostly of lime-cement plaster on concrete together with veneered chipboard, surfaces that the operators described as noticeably reverberant. Figure 1 shows the source standing in the hall during the campaign.

Figure 1: Omnidirectional dodecahedron loudspeaker mounted on a subwoofer, used as the sound source in the concert hall.

Every bounding surface and every large object, including the stage, bar and podium, was measured with a laser distance meter, and a three-dimensional model was built in the open-source software FreeCAD to obtain the individual surface areas. Each surface was assigned a material, and the matching octave-band absorption coefficients were taken from the German room-acoustics standard (DIN 18041), whose tabulated values derive from reverberation-room measurements made to a separate international standard.[6][7] The equivalent absorption area of the room in each band was then formed as the sum of every surface area multiplied by its absorption coefficient. Table 1 lists the principal materials, their areas and their coefficients, together with the resulting equivalent absorption area per band.

Table 1: Principal interior surfaces of the concert hall with their areas and octave-band sound absorption coefficients α (after DIN 18041), and the resulting equivalent absorption area A. The room volume was 664.75 m^3.

Surface material	**Area S (m^2)**	**Sound absorption coefficient α per octave band (Hz)**					
		125	**250**	**500**	**1000**	**2000**	**4000**
Veneered chipboard on solid backing	233.70	0.04	0.04	0.05	0.06	0.06	0.06
PVC flooring (2.5 mm) on concrete	173.46	0.01	0.02	0.01	0.03	0.05	0.05
Lime-cement plaster	130.52	0.03	0.03	0.02	0.04	0.05	0.05
Stage molton curtain (500–600 g/m^2)	73.98	0.12	0.35	0.55	0.72	0.70	0.65
Marble and tiles	13.04	0.01	0.01	0.02	0.02	0.03	0.03
Insulating glazing (windows)	10.44	0.28	0.20	0.11	0.06	0.03	0.02
Melamine foam (50 mm)	2.21	0.16	0.56	0.87	0.96	0.97	0.97
Equivalent absorption area A (m^2)	**637.35**	**27.3**	**46.1**	**60.0**	**80.7**	**83.9**	**80.0**

Reverberation times were calculated with the Sabine equation, $RT = 0.163\ V/A$, applied separately to each octave band, where RT was the reverberation time in seconds, V the room volume in cubic metres, A the equivalent absorption area of the band in square metres, and the constant carried units of seconds per metre.[1]

The measurements followed the procedure of the international standard for performance spaces, which the Swiss building-acoustics standard (SIA 181) adopts directly.[5][8] Sound was radiated by an omnidirectional dodecahedron loudspeaker, the most common design for approximating a non-directional source, since a directional source would bias the decay.[9] To reach the lowest bands with sufficient level, the dodecahedron was combined with a subwoofer. The room response was captured with a calibrated pressure microphone of omnidirectional characteristic[10] connected through a digital mixing console that served as the analogue-to-digital interface, and the signals were generated and analysed in the free measurement software Room EQ Wizard.[11] A logarithmic sine sweep covering 50 to 10000 hertz was reproduced at about 85 decibels so that the decay curve stayed well above the background noise. The acoustic centre of the source was set 1.5 metres above the floor. The source occupied three representative positions, on the stage and in the left and right audience areas, and the microphone was moved over nine positions for the stage source and eight for each audience source, all keeping the minimum spacing required by the standard. Figure 2 shows the source and microphone positions in plan.

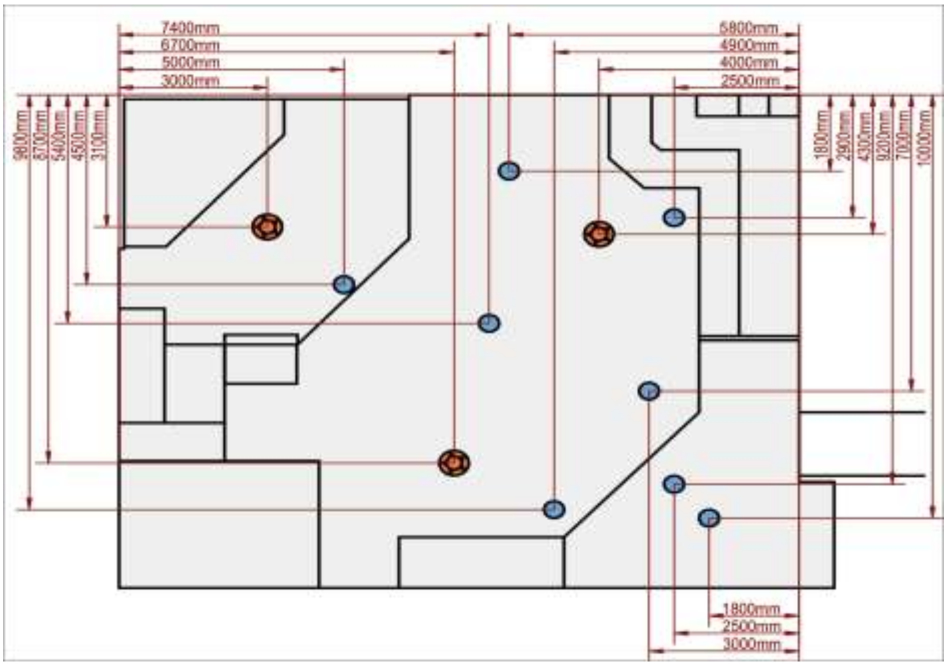

Figure 2: Plan of the concert hall showing the three source positions (dodecahedron symbols) and the microphone positions (circular markers). Dimensions are given in millimetres.

For every source-receiver combination the late decay was evaluated between -5 and -35 decibels to give the quantity denoted T30, and the reverberation time was obtained by doubling it. This late-decay evaluation was chosen because it is less sensitive to early reflections and to background noise than a full 60-decibel decay.

Statistical Analysis

For each source position the reverberation times were averaged arithmetically across the microphone positions in every octave band, which gave one spatially averaged value per source. The mean of the three source positions was then taken as the representative value for the room, in line with the spatial-averaging principle of the measurement standard. Twenty-five impulse responses were evaluated in total. The deviation between calculation and measurement was expressed as the difference between the measured and the calculated value relative to the calculated value, in per cent. A difference of about five per cent, the just noticeable difference for reverberation time stated in the standard, was used as the threshold below which a deviation carried little practical weight.

RESULT

The equivalent absorption area rose with frequency, from 27.3 square metres at 125 hertz to a plateau of about 80 to 84 square metres above 1000 hertz, which reflected the stronger absorption of the plastered surfaces, the flooring and the stage curtain at mid frequencies (Table 1). Because the calculated reverberation time is inversely proportional to this area, the Sabine values fell steadily across the spectrum, from 3.97 seconds at 125 hertz to roughly 1.3 seconds above 1000 hertz.

The measured reverberation behaved differently. Rather than falling monotonically, it rose from about 1.6 seconds at 125 hertz to a maximum near 2.3 seconds at 1000 hertz and then decreased towards the highest band, the shape typical of a hard room whose low frequencies are governed by mechanisms other than simple surface absorption. Figure 3 presents the measured curves for the three source positions together with the calculated values. The stage position produced the longest reverberation at mid and high frequencies, with a six-band mean of 2.14 seconds, whereas the two audience positions were shorter and almost identical at 1.89 and 1.92 seconds. Their fuller furnishing, with the bar and the podium acting as additional scattering and absorbing structures, accounts for the difference.

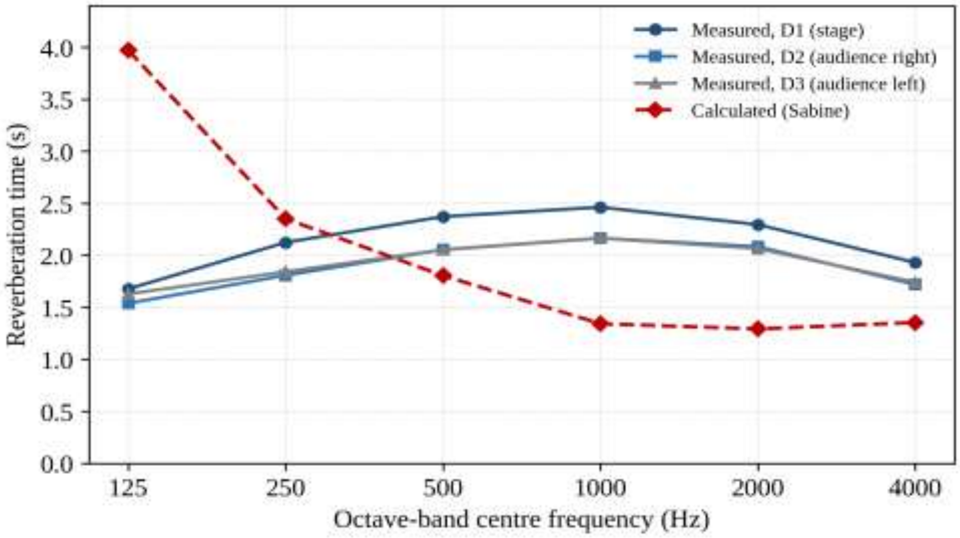

Figure 3: Measured reverberation time at the three source positions (D1 stage, D2 audience right, D3 audience left) and the reverberation time calculated with the Sabine equation, per octave band.

The two approaches crossed between 250 and 500 hertz. Below the crossover the calculation predicted far more reverberation than was measured, and above it the calculation predicted too little. The deviations are summarised in Figure 4. At 125 hertz the measured reverberation fell 59 per cent below the Sabine value, and at 250 hertz 18 per cent below it; the smallest deviations occurred at 250 and 500 hertz. Even there the gap of 18 to 20 per cent remained well above the five per cent just noticeable difference, so no individual band truly agreed. From 1000 hertz upward the measurement rose above the calculation by wide margins, 69 per cent at 1000 hertz and 66 per cent at 2000 hertz. Averaged over the six bands the measured and calculated single-number values were almost identical, 1.98 against 2.02 seconds, a difference below two per cent and within the just noticeable difference.

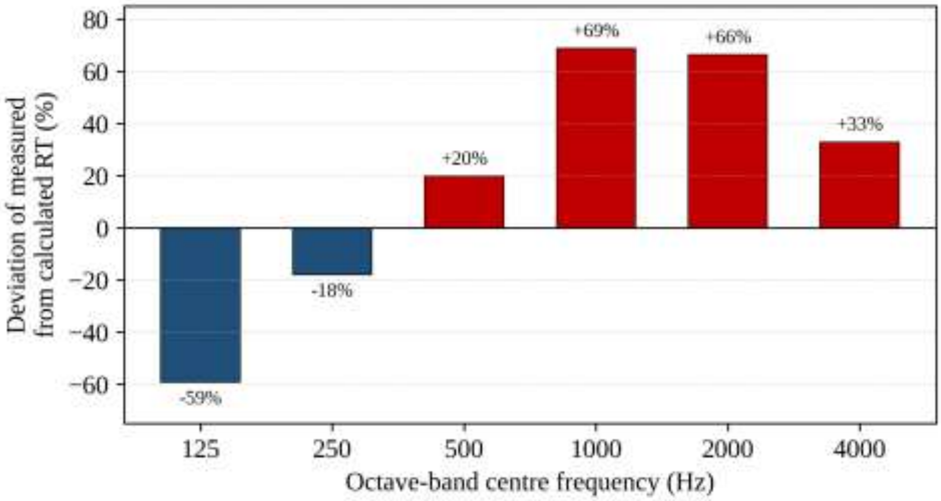

Figure 4: Deviation of the measured reverberation time, averaged over the three source positions, from the Sabine calculation, per octave band. Positive values indicate that the measured value exceeded the calculation.

DISCUSSION

The broadband agreement and the band-by-band errors pointed in opposite directions. The single-number reverberation times differed by less than the just noticeable difference, which on its own would suggest that the Sabine calculation described the room well. The frequency analysis shows that this agreement was coincidental, the product of a strong over-prediction at low frequencies cancelling an almost equally strong under-prediction at middle and high frequencies. A single-number rating is therefore an unreliable basis for judging this room, and any treatment guided by it alone would miss where the real problems lie.

At 125 hertz the calculation overestimated the reverberation by more than half. The Sabine model assumes a diffuse field with a high density of room modes. In a room of this size the Schroeder frequency, which marks the transition to such a field, lies near 100 hertz, so the 125 hertz band sits at the lower edge of the model's validity, where sparse discrete modes still shape the decay rather than statistical absorption.[2] The raised podium opposite the stage may add to this by forming a low, semi-enclosed sub-volume that stores and releases low-frequency energy, a behaviour the single-volume Sabine equation cannot represent.[4] The measured decay at 125 hertz was consequently much shorter than the calculation implied.

The under-prediction from 1000 hertz upward points in a different direction. Here the measured reverberation was longer than calculated, which indicates that the room absorbed less than the tabulated coefficients suggested. Absorption coefficients are determined in a reverberation room under idealised mounting conditions, and values carried from such tables to installed surfaces are known to hold substantial uncertainty.[3][12] Tall, hard, parallel walls also favour specular reflections and a field that is not fully diffuse, both of which lengthen the measured decay relative to the diffuse-field assumption. The residual directivity of the dodecahedron at high frequencies may add a small further difference, although it is unlikely to account for deviations of this size.[9] Absorption at a real boundary also depends on the angle of incidence and on local edge and flow effects, which a single tabulated coefficient cannot represent.[13]

Several limitations should be kept in mind. The hall was measured unoccupied, whereas an audience would add considerable absorption and shorten the reverberation, above all at mid and high frequencies. The comparison rests on a single measurement campaign and on absorption coefficients taken from tables rather than determined for the actual surfaces, and no uncertainty band was placed on those tabulated values, so the band-level deviations are best read as indicative. Air absorption was not included in the calculation, in keeping with the basic Sabine approach; at the highest bands it would have raised the predicted absorption slightly and therefore cannot account for the measured under-prediction. The Sabine equation was used in preference to the Eyring formulation, a choice justified here because the area-weighted mean absorption coefficient ranged only from 0.04 at 125 hertz to 0.13 at 2000 hertz, a regime in which the two formulations practically coincide. Decay-curve curvature, which can arise where a coupled sub-volume is present, was not analysed separately, and this qualifies the interpretation of the lowest band. The deviation metric, finally, refers all differences to the calculated value, so the low-frequency and high-frequency errors are expressed on a common basis.

For practical purposes the findings support a combined approach. A Sabine calculation from a careful surface survey gives a sound first estimate of the broadband reverberation and is inexpensive to produce. It does not, however, reveal the frequency-dependent imbalance that decides how a room actually sounds, and in this case it would have hidden a pronounced low-frequency problem behind an apparently ideal average. Measurement remains necessary whenever an existing room is to be assessed or optimised.

CONCLUSION

The reverberation time of the concert hall was calculated with the Sabine equation and measured according to the international standard, band by band, between 125 and 4000 hertz. The broadband single-number values agreed to within two per cent, yet the individual octave bands revealed deviations of up to about 69 per cent, with the calculation overestimating the reverberation at low frequencies and underestimating it at middle and high frequencies. The close average agreement was therefore coincidental, the result of low- and high-frequency errors of opposite sign cancelling out. The Sabine equation remains a useful first estimate for room-acoustic planning, but its prediction of the equivalent absorption area is least reliable exactly where acoustic treatment is usually required. Dependable optimisation of an existing room calls for both calculation and measurement together.

Declaration by Authors

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Conflict of Interest: No conflicts of interest declared.

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