Analysis of Reverberation Time Field Measurement Results in Building Acoustics

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Abstract — **Sound level difference between two rooms depends on both sound reduction between the rooms and their acoustical properties, such as the absorption in the receiving room. In order to abstract the influence of the rooms and assess only the sound reduction between them, relevant building acoustics standards offer two ways of normalizing a measured sound level difference – according to the reverberation time and the equivalent sound absorption area in the receiving room. In both cases measurement procedure requires reverberation time measurements in the receiving room, from which the equivalent sound absorption area can be assessed using Sabine's formula. This paper analyses more than 300 results of reverberation time field measurements and provides an insight into its typical values in buildings. The measurements are done by five teams of building acoustics engineers, mostly involved in the international EU COST Action TU0901. The results are gathered in a unique database as a part of the STSM (Short Term Scientific Mission).**

Keywords — **building acoustics, equivalent sound absorption area, field measurements, reverberation time.**

I. Introduction

SOUND insulation measurements, besides a sound level difference between source and receiving room, normally require reverberation time measurements [1], [2]. Reverberation time inside the receiving room is used for obtaining standardized and normalized sound level difference values, thus subtracting the acoustical properties of the receiving room, which, as well, contribute to the measured sound level difference. This is done in two generalized forms:

$$X_{nT} = L_1 - L_2 + 10\log_{10}(T/T_0)\,, \quad (1)$$

$$X_n = L_1 - L_2 - 10\log_{10}(A/A_0)\,, \quad (2)$$

where X is a sound insulation descriptor, such as sound level difference (D). The same holds for impact sound pressure level (L), apart from the opposite sign of normalizing term on the right-hand side of the equations (1) and (2). L_1 and L_2 are sound levels in a source and receiving room, respectively, T is reverberation time in receiving room, T_0 is the reference reverberation time (0.5 s) and A_0 is the reference equivalent sound absorption area (10 m^2). In equation (2) reverberation time is implicitly given through the equivalent sound absorption area (A), which is calculated using Sabine's formula:

$$T = 0.16\frac{V}{A}\,, \quad (3)$$

with V denoting room volume, and, therefore, obtained from reverberation time measurements as well. Normalized (X_n) and standardized (X_{nT}) values should in this way refer to the case of common furnished residential rooms, reverberation time of which should be, according to [1] and [2], equal to 0.5 s and more or less independent of frequency and volume of the room. Typical equivalent sound absorption area is considered to be 10 m^2. Validity of both of these values is inspected in this paper, through the presentation of reverberation time measurement results, obtained in a large number of furnished residential rooms. An additional goal of the paper is to provide an insight into the common values of reverberation time and equivalent sound absorption area and their range in building acoustics practice, in residential and non-residential, furnished and unfurnished rooms of various sizes.

Sound insulation measurements are usually done in third-octave bands, with a minimum range of 100 to 3150 Hz. However, new standard proposals in building acoustics [3], [4] provide a basis for sound insulation measurements in the extended frequency range – from 50 to 5000 Hz and even make such measurements obligatory. For example, calculating single-number parameters X_{living} and $X_{traffic}$ according to ISO/NWIP 16717 [4], which is to be adopted in 2015, requires measurements in such a full frequency range. In addition, many European countries consider changing their current sound insulation regulative to make field measurements of sound insulation in the extended frequency range mandatory.

Unfortunately, reverberation time measurements in the extended frequency range are very often associated with difficulties, which give rise to large measurement uncertainties, especially at low frequencies. The causes of such difficulties can be found in all aspects of measurements:

- measurement conditions (with a background noise level generally increasing at low frequencies),
- measurement techniques (for example selectivity of the implemented fractional octave-band filters [5]),
- physical phenomena (such as standing waves).

Furthermore, current standards and literature still lack data about the measurements and their uncertainty at frequencies below 100 Hz. The situation is somewhat

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easier with sound level measurements, although the uncertainties at low frequencies can still be high due to the uneven spatial distribution of sound energy throughout the room [6], [7]. However, the focus of this paper will be only on reverberation time field measurements in the extended frequency range and the equivalent sound absorption area values derived from them.

Reverberation time has been traditionally measured by implementing interrupted random noise technique, but new methods are also proposed and standardized [8], based on room impulse response measurements. They are considered to provide higher effective signal-to-noise ratios by taking the advantage of certain properties of deterministic excitation sequences they incorporate (usually a maximum length sequence or swept-sine). Still, it seems that the new methods have not been widely accepted in building acoustics practice yet, as majority of the measurements, the results of which are presented here, implemented classical interrupted noise technique.

The aim of this paper is to inspect reverberation time and equivalent sound absorption area values in buildings. Its focus is on the analysis of more than 300 reverberation time field measurement results, obtained by following procedures according to the relevant standards in the field of building acoustics. Next section describes in more detail the database consisting of field measurement results. The database has been statistically treated and the results are given in section III. The last section summarizes several conclusions based on the conducted analysis.

II. The Database

The analysed database consists of 327 field reverberation time measurements results, obtained by five independent teams of engineers. All the measurements are done for the purposes of façade sound insulation measurements according to ISO 140-5. The unique database of the measurement results is formed during the STSM (Short Term Scientific Mission) as a part of the activities on the international EU COST Action TU0901. The objective of the Action is to propose sound insulation descriptors to be widely adopted by European countries in the future. Besides the basic characteristics of the rooms (such as volume, room type and furniture presence), the database contains reverberation time values measured in third-octave bands, in the extended frequency range from 50 Hz to 5000 Hz. The sound source was a loudspeaker emitting an interrupted third-octave filtered white noise sequence. Reverberation time is generally calculated by the use of specialized software, but in many cases the results were also manually checked for calculation errors. Although the measurements were made in the extended frequency band, due to the large measurement uncertainty at low frequencies (especially below 100 Hz) and the low selectivity of the low frequency filters used, the results in these frequency bands should be taken with reserve.

Room sizes vary from 10.8 m^3 to 380.3 m^3 and both furnished and unfurnished rooms are included. Distribution of room volumes is given in Fig. 1, based on which all analysed rooms are divided into four categories according to their size – less than 25 m^3, between 25 and 50, 50 and 100 and above 100 m^3. For better clarity of the graph, the abscissa values are limited to 200 m^3, so four rooms from the database with larger volumes are omitted. Table 1 shows the total number of rooms in each category.

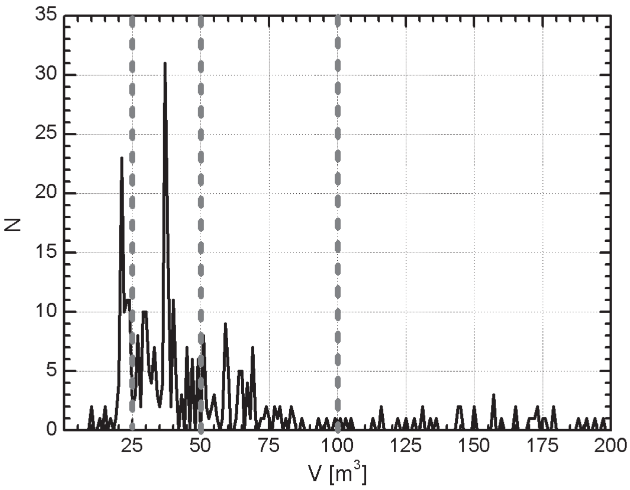

Fig. 1. Distribution of room volumes (four non-residential rooms larger than 200 m^3 are omitted).

Table 1: Room volume categories.

Volume [m^3]	*No. of rooms (residential + non-residential)*
$V \leq 25$	63 (63+0)
$25 < V \leq 50$	148 (146+2)
$50 < V \leq 100$	74 (66+8)
$V > 100$	42 (4+38)
Total	**327 (279+48)**

The rooms are also divided according to building unit typology to residential (279) and non-residential (47 schools and 1 hospital). Almost all large rooms (with volumes above 100 m^3) belong to non-residential units. Since, similarly, almost all smaller rooms belong to residential units, 100 m^3 can be rather safely determined as a boundary value separating residential and non-residential rooms.

It follows from the relevant building acoustics standards [1], [2], by inserting $T=T_0$ and $A=A_0$ in equation (3), that a typical residential room volume is about 31 m^3. The average volume of analysed rooms is 57.2 m^3 (as can also be seen in Table 2) with 41.8 m^3 for residential and 146.3 m^3 for non-residential rooms, so 31 m^3 might seem a bit on the low side. Still, majority of the residential rooms (more than half of them) are of the size between 25 and 50 m^3.

The analysed rooms are also divided by the furniture presence into furnished and unfurnished. As the sound insulation measurements are usually conducted in unfurnished rooms, their number in the database is larger – 151, while that of the furnished ones is 91. Rest of the rooms lack this kind of data, so they had to be omitted from the analyses taking into account room furnishing.

III. Reverberation Time and Equivalent Sound Absorption Area Measurement Results

After forming the database, the measurement data were subjected to basic statistical analysis. Reverberation time and equivalent sound absorption area values, both in third-octave bands and weighted, were considered. Equivalent sound absorption area values were calculated from reverberation time and volume data, by using equation (3). The following sections present the results of the analysis. Apart from the obtained insight into typical values of reverberation time and equivalent sound absorption area in buildings, the influence of room type, size and furnishing on the two parameters' values is assessed through the division of the rooms, as described in Section II. Variation of the parameters' values is also assessed in the rooms similar in terms of volume and furniture presence.

A. Reverberation Time

Average reverberation time in 91 furnished and 151 unfurnished rooms, which are also organized in volume categories given in Table 1, is given in Fig. 2. Rooms with volumes above 100 m^3 are omitted because of the insufficient number of measurements in both sub-databases of furnished and unfurnished rooms. The number of analysed unfurnished rooms below 25 m^3 is 9 while that of furnished rooms between 50 and 100 m^3 is 13. All other room volume categories are covered with at least 30 measurement results. Average reverberation time of furnished rooms at middle frequencies is around 0.5 s for volumes below 50 m^3, complying well with the reference value T_0 from equation (1), but around 0.7 s in larger rooms, above 50 m^3. In both cases its value increases below 100 Hz to about 1 s in the lowest third-octave bands, thus making the reverberation time at low frequencies more frequency dependable.

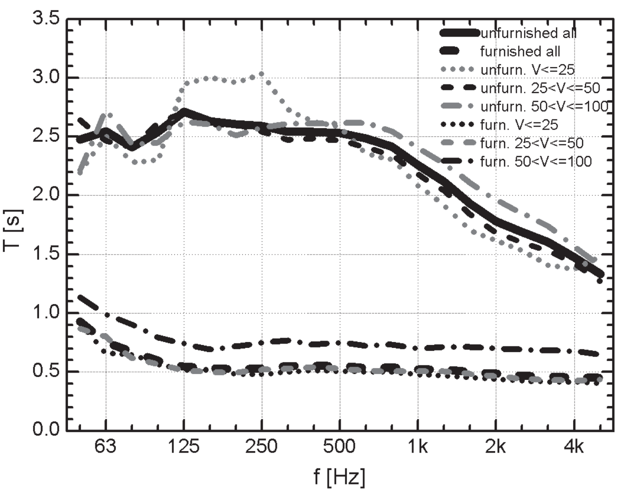

Fig. 2. Measured reverberation time values in furnished and unfurnished rooms of different volumes.

Average reverberation time seems to be less volume dependent in unfurnished rooms and is around 2.5 s below 500 Hz, and drops to 1.3 s at 5000 Hz, as a nearly linear function of third-octave bands central frequency. The reasons for this decay are higher absorption at room surfaces and dissipation in air at high frequencies. Dispersion of the results is somewhat larger in small unfurnished rooms (V<25 m^3), although this can be due to the low number of such rooms covered by the analysis (only 9). In the unfurnished rooms, evident is also a small dip of reverberation time values around 80 and 100 Hz third-octave bands. This might be a consequence of resonance effects in doors and windows of the rooms, since all analysed rooms had at least one façade wall. It is well known that the sound reduction index of glazing façade elements drops around their resonance frequencies. Sound energy at these frequencies, escaping through the doors and windows, will then cause a faster sound level decay inside the room and lower reverberation time values. The effect might be enhanced by the room eigenmodes occurring in these frequency bands, and which are formed between room surfaces, one of which includes the glazing elements.

The standard deviation of measured reverberation time values is given in Fig. 3. It is nearly constant in furnished rooms – around 0.25 s for volumes less than 50 m^3 (rising to 0.4 s only in the lowest third-octave bands) and 0.4 s for larger rooms. On the other hand, the standard deviation in unfurnished rooms decreases approximately linearly with the third-octave central frequencies, from 1 to 0.3 s (a grey thick line represents linear approximation of the unfurnished rooms curve). It should also be noted that, compared to the average reverberation time, these values are lower than in furnished rooms. Since a different absorption value in rooms of similar sizes produces a different reverberation time in them, such large dispersion in furnished rooms, with a standard deviation around 50% of the average value, points to the large dispersion of equivalent sound absorption area values in them, depending on the acoustical properties of furniture itself.

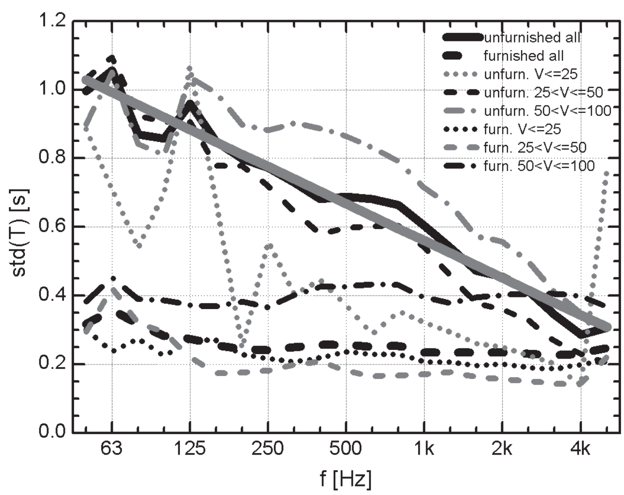

Fig. 3. Standard deviations of reverberation time values given in Fig. 2 (grey thick line represents the linear regression for the unfurnished rooms curve).

B. Equivalent Sound Absorption Area

According to the Sabine's formula, given in equation (3), equivalent sound absorption area in the analysed rooms can be assessed from their volumes and reverberation time values. The results are shown in Fig. 4.

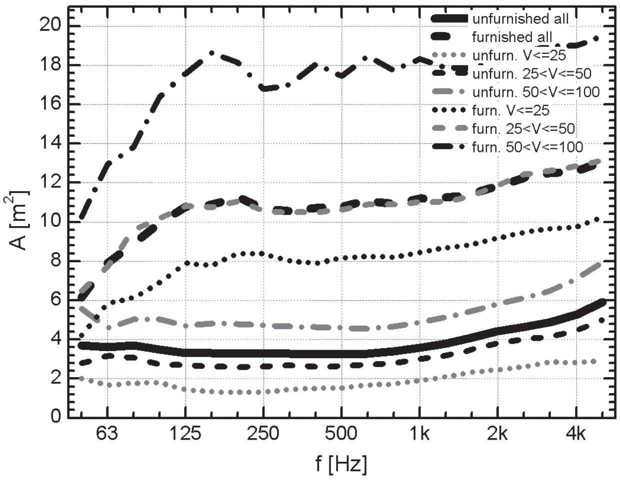

Fig. 4. Equivalent sound absorption area values in furnished and unfurnished rooms of different volumes.

Average equivalent sound absorption area in unfurnished rooms is around 1 to 5 m^2, depending on the room volume and shows little frequency dependence, apart from the increase above 1 kHz. On the other hand, equivalent sound absorption area values in furnished rooms, besides the similar increase at high frequencies, show a deep decay below 125 Hz. This is also evident from reverberation time values shown in Fig. 2. However, reverberation time varies slightly in unfurnished rooms of different sizes (see Fig. 2), due to strongly volume dependent equivalent absorption area. In furnished rooms average equivalent sound absorption area is around 11 m^2 at middle frequencies (the reference value in ISO 140 being A_0=10 m^2), but taking values between 8 m^2 (rooms below 25 m^3) and 18 m^2 (rooms above 50 m^3), with about half the values at the lowest frequencies.

C. Single-number Values of Reverberation Time and Equivalent Sound Absorption Area

According to ISO 3382 [9] reverberation time can be expressed as a single-number quantity by averaging its values in third-octave bands from 400 to 1250 Hz. This is done for all the analysed rooms and the results are presented in Table 2. Besides the average volume, reverberation time and equivalent absorption area in the rooms, the standard deviations of calculated values are also given. While single-number reverberation time in furnished rooms of various size takes values between 0.5 and 0.7 s, it seems to be volume independent, around 2.4 s in unfurnished. In unfurnished rooms higher volume leads to the increase of total room surface and, thus, equivalent sound absorption area, so their ratio, which determines reverberation time according to equation (3), can stay about the same. In furnished rooms equivalent absorption area depends on the absorption properties of the furniture more than the bare walls, so the increase of absorption will not follow the increase of the volume to the same extent as in the case of unfurnished rooms.

Reverberation time of 2.4 s in unfurnished rooms gives, according to equation (3), A/V ratio of 0.067. In Fig. 5,

TABLE 2: AVERAGE VOLUME OF THE ANALYSED ROOMS, REVERBERATION TIME AND EQUIVALENT SOUND ABSORPTION AREA

	all	residential	non-residential	furnished				unfurnished			
				all	V<=25	25<V<=50	50<V<=100	all	V<=25	25<V<=50	50<V<=100
V [m^3]	57.2	41.8	146.3	33.1	21.9	31.2	67.1	47.7	24.2	38.7	65.7
σ(V)	48	19.6	64.5	19.1	2.1	4.5	10.3	17.9	1	5.8	10.8
T [s]	1.6	1.7	1.5	0.5	0.5	0.5	0.7	2.4	2.3	2.3	2.5
σ(T)	1	1	0.84	0.24	0.22	0.17	0.4	0.63	0.32	0.55	0.79
A [m^2]	7.9	6.1	18.2	10.9	8.2	10.7	17.9	3.4	1.7	2.8	4.7
σ(A)	7.4	5.21	9.8	6.2	3.04	3.87	7.23	1.76	0.33	0.73	2.31

representing the equivalent sound absorption area of all analysed unfurnished rooms as the function of volume, this ratio is drawn as the grey line. Apart from several cases with a rather high absorption area value, which might also be a consequence of measurement inaccuracy, all the assessed values of equivalent sound absorption area are scattered around the grey line. Of course, such a linear relation between the two quantities would be too approximate. Since the absorption depends on acoustic properties of the room surfaces and especially the doors and windows, two or even more times the difference of the absorption area values (and, consequently, the reverberation time) in unfurnished rooms of the same size can occur. However, this simple expression can be a good indicator of the expected values in practice. Especially since the building acoustics measurements are mostly done in unfurnished rooms.

D. An Example of the Dispersion of Reverberation Time Values in Rooms of the Same Size

To illustrate the dispersion of reverberation time values independently of room volume, Fig. 6 shows reverberation time measured in third-octave bands from 50 Hz to 5 kHz in 19 unfurnished bedrooms of almost the same volume (38±0.5 m^3) and similar dimensions. Thus, the differences at low and middle frequencies are expected to occur mostly due to different absorption properties of room surfaces and (if there are any) sound insulation properties of doors and windows. The thick grey line represents average values for all 19 measurements. While the differences decrease with frequency, at the lowest frequency bands reverberation time shows values in the range of 1 to more than 4 s, matching the discussion about the equivalent sound absorption area value spread from previous subsection. Observable again is the drop of the curves on the graph around 80 Hz third-octave band. By comparing Fig. 6 with the results from Fig. 2 for unfurnished rooms with volumes between 25 and 50 m^3, it can be seen that the values of both curves are very similar above 1 kHz, but getting about 0.5 s higher below 500 Hz in the case of Fig. 6. The values around the dip at 80 Hz seem to be about the same in both cases.

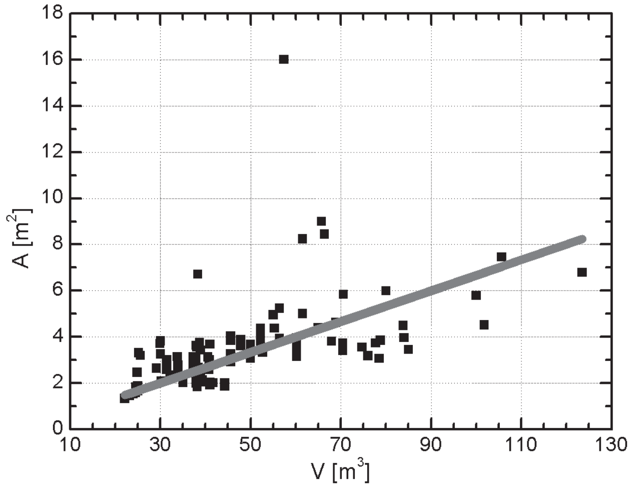

Fig. 5. Equivalent sound absorption area in unfurnished rooms as a function of room volume (grey line represents the linear approximation according to the average reverberation time of 2.4 s).

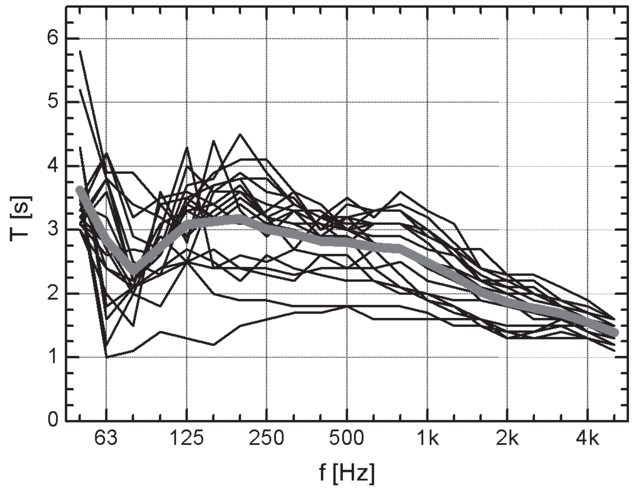

Fig. 6. Reverberation time measured in 19 unfurnished rooms of the volume 38 ± 0.5 m^3.

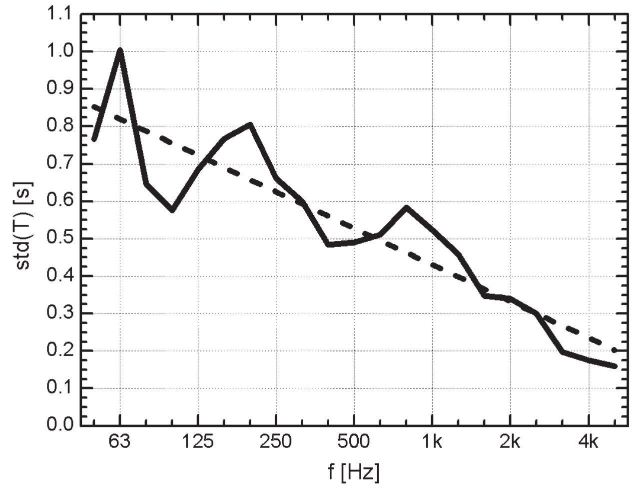

Fig. 7. Standard deviation of reverberation time presented in Fig. 6 and its linear regression line.

The standard deviation of reverberation time values in third-octave bands is given in Fig. 7 and, apart from being about 0.1 s lower, practically matches the one from Fig. 3, despite the rooms being of nearly the same size. It has an obvious decay towards high frequencies (represented with linear regression – the dashed line). Again, the increase of standard deviation towards low frequencies is expected to be related to the differences in the absorption properties of the walls and doors' and windows' types and sizes, that is, the differences in the equivalent sound absorption area in the unfurnished rooms. At very low frequencies the differences can partially be a consequence of higher measurement uncertainty. As a conclusion, setting the room volume to a fixed value almost did not lower the reverberation time values spread at all, compared to the case of rooms of arbitrary size.

IV. Conclusion

The presented analysis has shown some typical values of reverberation time and equivalent sound absorption area in the rooms of various types, sizes and acoustic properties. Due to the large database of measurement results, a majority of practical cases in field sound insulation measurements is covered and several conclusions can be derived. First, almost all of the analysed rooms belonging to residential building units have volume below 100 m^3, while, on the other hand, most of the non-residential rooms, such as school classrooms, exceed this value. Therefore, 100 m^3 seems to be a reasonable separating value between residential and non-residential room types. Although the division is not without exceptions, it is indicative in terms of the range of residential room sizes.

Average reverberation time in the unfurnished rooms covered by the analysis is about 2.5 s in third-octave bands below 500 Hz and linearly decaying to 1.3 s at 5000 Hz. In the furnished rooms with volumes below 50 m^3, reverberation time is nearly constant above 125 Hz (0.5 s) and increases to 0.9 s at 50 Hz. In larger furnished rooms, it takes about 0.3 s higher values in all third-octave bands. The assumption that reverberation time value in furnished residential rooms is around 0.5 s and independent of the room size and frequency is limited to the cases of not too large rooms (below 50 m^3) and above 100 Hz. While the standard deviation of measured reverberation time values in furnished rooms is about 0.25 s in all frequency bands, in unfurnished rooms it linearly decreases with third-octave bands' central frequencies, from around 1 to 0.3 s. Relative to the average reverberation time, this is about 60% in furnished and 40 to 25% in unfurnished rooms.

Equivalent sound absorption area shows almost the same frequency dependence (apart from being inversely proportional), but is even more volume dependent. The value of 10 m^2 seems to be relevant only for middle-sized rooms (between 25 and 50 m^3) at middle frequencies. Total absorption in larger rooms reaches about 18 m^2, while in smaller ones it drops below 8 m^2. In all furnished rooms the equivalent sound absorption area shows both a strong decay below 125 Hz and a slow increase above 1 kHz. In unfurnished rooms, apart from the slight rise above 1 kHz, equivalent sound absorption area values are much more constant and take values between 1 m^2 in small and 5 m^2 in large rooms.

The implications of previous conclusions can be found in sound insulation measurements or predictions, where typical values of reverberation time (0.5 s) and equivalent sound absorption area (10 m^2) are used for obtaining normalized and standardized values, as in equations (1) and (2). One such example is assessment of a sound level inside a room from sound insulation value of separating partition and noise level behind it. A standardized sound pressure level increases with $10\cdot\log_{10}(T/T_0)$, while a normalized level decreases with $10\cdot\log_{10}(A/A_0)$. According to the dispersion of the results presented here, due to the difference between T_0 and A_0 values and real values of T and A in a room, dispersion of sound pressure level can be -1 to +2.5 dB in regular furnished rooms of various sizes. Since average reverberation time in unfurnished rooms is shown to be 2.5 s, a standardized sound pressure level should be expected to be about 7 dB higher than in furnished rooms, with small dispersion depending on volume. However, dispersion can be as large as ±3.5 dB in case of normalized values, due to equivalent sound absorption area varying between 1 m^2 to 5 m^2, depending on volume.

Finally, the spread of reverberation time measurement results is also examined on the sample of 19 unfurnished rooms of the same size and shape. Shapes of the reverberation time and standard deviation values curves mostly match the average curve of unfurnished rooms of various sizes, leading to the conclusion that the dispersion of reverberation time and equivalent sound absorption area values is large, even in unfurnished rooms of the same size.

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