# Inaccuracies in sound pressure level determination from room impulse response

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The integration over discrete squared room impulse response (RIR) leads to the sound pressure level (SPL). However, certain inaccuracies in SPL determination appear as a consequence of influences of finite integration upper limit (UL) and noise. Due to that, these influences are investigated using two types of RIRs: those generated by simulation and those measured in the room. The investigations show that for RIRs with sufficiently small noise floors (below −20 or −15 dB) acceptably small inaccuracies are obtained if the integration UL is placed at $T/3$ (alternatively at $T/4$). A more general solution is to set UL at the knee representing the point where main decay intersects noise floor. For even smaller inaccuracies, it would be better to set UL at the point somewhat before the knee called optimal UL. The influences of finite integration UL and noise can also be reduced by implementation of finite UL compensation and noise subtraction. © *2002 Acoustical Society of America.* [DOI: 10.1121/1.1426375]

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## I. INTRODUCTION

The room impulse response (RIR) represents one of the most important room characteristics. The corresponding processing of the RIR can yield various room quantities and measurement parameters.[1–3] The focus of this paper is the steady-state mean-square pressure, that is the sound pressure level (SPL), obtained by the integration over squared RIR from zero to infinity.[4,5] In practice, this infinite upper limit (UL) of integration must be transformed into finite UL.

It has already been theoretically shown, excluding the influence of background noise (in the following called noise), that the integration up to $T/3$ or $T/4$ in SPL determination results in acceptably small error.[6,7] As an extension to this result, investigations of the influence of integration UL together with the influence of noise are performed here on a practical basis. Namely, the inaccuracy in SPL determination due to the integration over RIR of finite length is quantified. Not only has the finite length of RIR an important influence on inaccuracy, but also it matters whether the reverberant sound or noise is dominant in the part of RIR where the UL is placed. So, the investigations include the influence of noise and its power using the RIRs with various signal-to-noise ratios (SNRs). Besides, the number of averages required in order to obtain defined accuracy of SPL is analyzed.

Various approaches for reducing the influences of finite integration UL and noise are implemented including the setting of suitable UL and additional processing. The latter involves two correction techniques: noise subtraction for reducing the influence of noise, and finite UL compensation for reducing the influence of finite integration UL.

The mentioned influences are investigated on two types of RIRs with exponential decay. The first is obtained by simulation, using a proposed mathematical model, which enables generation of RIRs with known characteristics. The second type of response represents the RIRs measured in a particular room by the implementation of Maximum Length Sequence (MLS) technique[5–8] for a measurement system.[3,9]

## II. SPL DETERMINATION FROM RIR

The integration over squared RIR $h^2(\tau)$ results in the steady-state mean-square pressure

$$p^2(t)=G\int_0^\infty h^2(\tau)\,d\tau, \tag{1}$$

where $G$ is proportional to the source power.[4,5] When the MLS technique is implemented for measurement, the RIR represents a correlation function since it is obtained by cross-correlation of excitation signal and the response.[8] In the SPL determination from the RIR, the most important step is to calculate the overall energy as precisely as possible.[6,7] Of course, the integration UL cannot be infinite in practice, due to the finite length of measured RIR. As a consequence of this, all of the energy is not included in the calculation. However, since the RIR decays exponentially, most of the energy is concentrated in the response beginning. In this way, the integration over the early part of the RIR can yield an approximately correct result.[6] Nevertheless, there is a question of where the UL of integration should be set to obtain acceptable inaccuracy of SPL determination.

This problem becomes more complicated due to the influence of noise. The impulse decay representing the logarithmic plot of squared RIR consists of two parts: the first part where reverberation sound is dominant and the second part where the noise is dominant, as illustrated in Fig. 1. The point of intersection of these parts is the knee. In the vicinity of the knee, a significant influence of both reverberant sound and noise exists. In SPL determination, the integration UL should be set at the first part of RIR where reverberant sound is dominant. On the other hand, if the UL is placed at the

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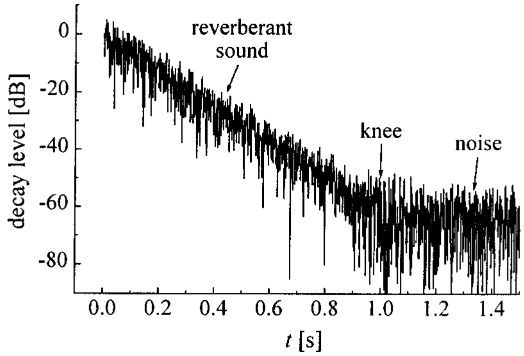


FIG. 1. The impulse decay of the simulated RIR with noise floor of −60 dB.

second part of RIR, the energy of the noise is added to the energy of reverberant sound, leading to bigger SPL than the right value. The energy of noise can also affect the accuracy of SPL determination if the UL is near the knee. In this case, by using only the first part of RIR for integration, UL is dislocated toward the response beginning and the length of the useful part of the response is further reduced, especially when noise has relatively big power.

## III. INACCURACIES OF SPL DETERMINATION IN SIMULATED RIRS

### A. Generating simulated RIRs

The most convenient way to investigate the influences of integration UL and noise is to use RIRs whose characteristics are all known and whose parameters can be controlled. Such RIRs can be generated by simulation, that is, by a corresponding mathematical model. For this purpose, the mathematical model given by the following expression

$$h(t)=\mathrm{sgn}(n_1(t))[e^{-kt/2T}r(t)+\sqrt{a}n_2(t)], \tag{2}$$

is used here, where $r^2(t)$ is a unit-mean multiplicative random process modeling fluctuations due to multiple reflected paths, $a$ is the noise floor power, and $n_i(t)$ are the unit-variance noise processes. This model is based on a simple model for the squared RIR from Ref. 10. The time constant is changed here so that the impulse decay excluding the fluctuations and noise has the value of −60 dB for $t=T$, which is obtained for $k=13.815\,511$. Also, the model is extended by sgn function

$$\mathrm{sgn}(n_1(t))=\begin{cases}+1, & n_1(t)\geqslant 0\\ -1, & n_1(t)<0\end{cases}, \tag{3}$$

so that the simulated RIR comprises both positive and negative amplitudes in the part where the reverberant sound is dominant. This function does not influence the squared RIR remaining the same as in the mentioned simple model,[10] because it affects only the sign.

The process $r(t)$ is modeled as a Rayleigh fading process since it exhibits many of the characteristics of actual RIRs.[10] So, a random variable $R$ is postulated in such a way that $R^2$ has an exponential probability density. The variable $R$ can be generated as $R=\sqrt{(X^2+Y^2)/2}$, where $X$ and $Y$ are two independent zero-mean, unit-variance, normal random variables. The noise processes are modeled using Gaussian model. The mathematical model from Eq. (2) now enables generation of the simulated RIR, if there are four series of samples with Gaussian probability density. Two of them are used for noise processes $n_i(t)$ and the remaining two series are used for the random process $r(t)$. In order to obtain series with Gaussian probability density, a software module was developed.[3] The same set of four different series with Gaussian probability density can be used to generate RIRs with different SNRs by changing only the noise floor power, that is, parameter $a$ in Eq. (2). But, the RIRs can be generated using different sets of four series, as well.

The noise floor power in the measured RIR can be different, depending on the measurement and the environment, that is, on ambient noise. So, it can range from a small value in comparison to the signal power up to a value close to the signal power. For example, a large value of noise floor power can be obtained in a receiving room with high ambient noise, in the measurement of sound insulation. The noise floor powers of simulated RIRs used in investigations here are in such a range that the noise floor levels (in the following noise floors representing $10\log a$) are between −5 dB and −60 dB. The absolute value of noise floor is approximately equal to the response SNR calculated in a standard way as the ratio of signal power to noise power. The signal power is calculated from the beginning of RIR, while the noise power is calculated from the second part of RIR where noise is dominant. All the simulated RIRs have the length of 2000 samples, that is, they have a duration of 2 s if the relative sampling interval is set on value of 1 ms. Due to the convenience, the value of $T$ is set to 1 s. Figure 1 shows the impulse decay of a simulated RIR with noise floor of −60 dB, obtained by Eq. (2).

### B. Influences of integration UL and noise

The integration UL can be set at various points of an RIR depending on a particular response. So, the points of RIRs ranging from 0.005 s to 1.5 s with steps of 0.001 s are used here as ULs. In this way, the UL is placed at the part of an RIR where reverberant sound is dominant, as well as at the part where noise is dominant. The lower limit of integration is placed at zero, as it is defined in Eq. (1).

In SPL determination, the steady-state mean-square pressures obtained from the simulated RIRs with various noise floors by Eq. (1) for various ULs are normalized by the corresponding pressure. This pressure is calculated from the RIR with noise floor of –60 dB by the same Eq. (1) in which the UL is set at the knee, and it represents approximately the right value of pressure. Setting UL at the knee introduces smaller inaccuracy than setting UL at the end of RIR, which will be analyzed later. The normalization pressure can be calculated with even smaller inaccuracy from an RIR with lower noise floor, but the inaccuracy introduced by using the RIR with noise floor of −60 dB is already negligible (smaller than $10^{-5}$ dB). By implementation of the described normalization, it is found that the reference value of SPL corresponding to normalized, the right level is approximately 0 dB. In this way, the calculated levels for various ULs ($L_d$)

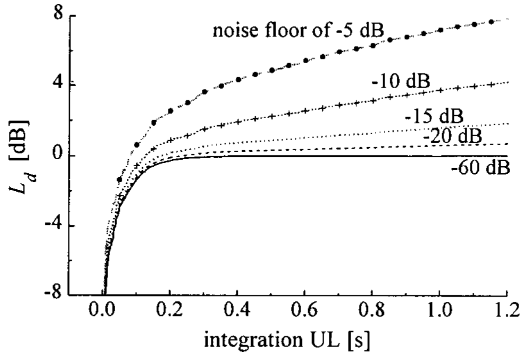


FIG. 2. The level deviations determined from simulated RIRs with various noise floors for various ULs.

directly represent the level deviations (the differences between the calculated levels and the right level).

The results of investigations show that considerable level deviation exists if the UL is set too close to the RIR beginning, so that a small range of response is integrated, as illustrated in Fig. 2. This deviation is negative because the calculated level is smaller than the right one, and it can be called "level decreasing." Level deviations above $-1$ dB appear in the RIR with noise floor of $-60$ dB, if the UL is placed at the points after 0.116 s (for that time, the RIR decays below $-7$ dB), while deviations above $-0.1$ dB appear for UL placed after 0.27 s. On the other hand, if UL is placed at the part of an RIR where noise is dominant or somewhat before, calculated level is bigger than the right one, that is, level deviation is positive and it can be called "level increasing." This level increasing becomes bigger as the UL is displaced toward the end of RIR and as the noise floor becomes bigger. It can reach a value of several decibels. This is why the integration UL should not be set in the part of an RIR where the noise is dominant.

The level deviation due to the finite integration UL can be theoretically obtained as

$$L_{dt}=10\log(1-e^{-kt_{ul}/T}), \qquad (4)$$

where $t_{ul}$ represents UL in time.[6,7] The level deviations determined from the simulated RIRs with relatively small noise floors are in good agreement with the deviation calculated by Eq. (4), as shown in Fig. 3(a). The noticeable differences in deviations in this example appear only if the integration UL is set close to the beginning of the RIR. Their absolute values drop below 0.3 dB for UL setting after 0.05 s, and they almost disappear for UL setting after 0.15 s. These differences are the consequence of response fluctuations. As the influence of fluctuations is bigger when the integration range is smaller, the noticeable differences exist only near the RIR beginning. On the other hand, the level deviations determined from the RIRs with higher noise floors (bigger than $-20$ dB) are considerably different from that calculated by Eq. (4). This is the consequence of the fact that the theoretically obtained level deviation in Eq. (4) does not take into consideration the influence of noise.

A procedure similar to that used in deriving Eq. (4) is implemented here to obtain theoretical level deviation, but

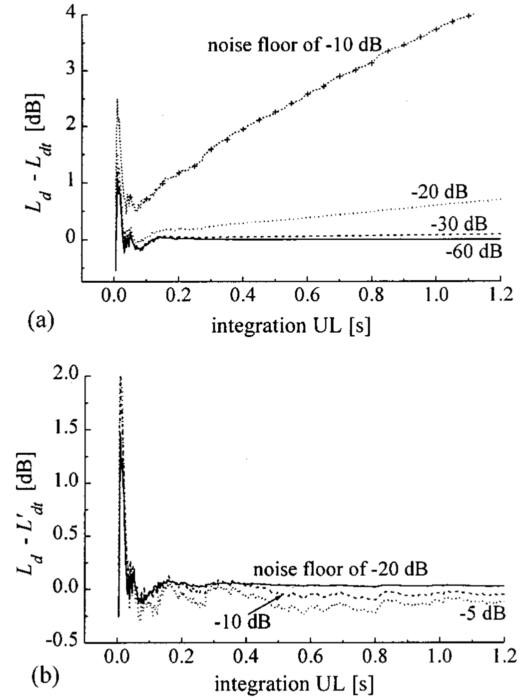


FIG. 3. The differences of the level deviations determined from the simulated RIRs with various noise floors and that one calculated by Eq. (4)(a), that is, by Eq. (6)(b).

including the influence of noise as well. For this purpose, the steady-state mean-square pressure is calculated by

$$p^2(t)=G\int_0^{t_{ul}}E\{h^2(\tau)\}d\tau=G\int_0^{t_{ul}}(e^{-k\tau/T}+a)d\tau, \qquad (5)$$

where $E\{h^2(\tau)\}$ represents the expectation of squared RIR, which can be understood to be over the ensemble of random processes,[10] $r(t)$ and $n_i(t)$ from Eq. (2). In this way, the random processes and the cross-term $(2e^{-k\tau/2T}\sqrt{a})$, which is obtained by squaring the response $h(\tau)$, disappear in the integrated function. The solving of the previous integral and adequate normalization lead to the following level deviation

$$L'_{dt}=10\log[1-e^{-kt_{ul}/T}+(k/T)at_{ul}]. \qquad (6)$$

The differences between the level deviations determined from simulated RIRs and the deviation calculated by Eq. (6) are now approximately equal to zero, as shown in Fig. 3(b), independent of the noise floor. Noticeable differences again exist only if the UL is placed close to the beginning of the RIR, as in Fig. 3(a), as explained above.

The described investigations were also performed on simulated RIRs generated using different sets of four series with Gaussian probability density. Level deviations obtained were similar to those presented in Fig. 2. However, there are relatively small differences between corresponding deviations especially in RIRs with higher noise floors, as shown in Fig. 4. Nevertheless, these differences do not greatly influence the conclusions.

Smaller level deviations, relative to those obtained by placing the UL at the part of the response where the noise is dominant, emerge if the UL is placed at the knee. Nevertheless, the calculated levels are again somewhat higher than the

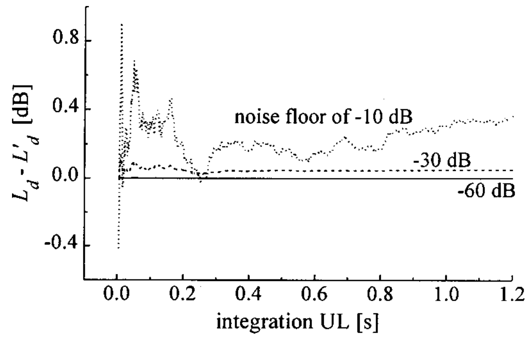


FIG. 4. The differences of level deviations determined from simulated RIRs generated by using two different sets of four series with Gaussian probability density ($L_d - L'_d$).

right level. This increase becomes bigger with increasing noise floor, rising to about 1 dB, as shown in Fig. 5. Because of that, in RIRs with relatively high noise floors it is better to set the integration UL at a point placed somewhat before the knee. In this way, since UL is displaced toward the response beginning, the reduction of level due to finite UL is increased and, at the same time, the level increase due to the noise is reduced. Thus, the calculated level is closer to the right one. Setting UL at the point where level decrease due to finite UL is equal to level increase due to noise, results in level deviation of 0 dB. This point can be called optimal point or optimal UL.

Table I shows the points of RIRs with various noise floors where the integration UL should be set in order to obtain the right level. In all the RIRs except in the response with noise floor of −5 dB, the level deviation is very small (or equal to 0) if the integration UL is set at the point representing 0.7 value of the knee. Thus, for example, in RIR with a noise floor of −15 dB, the knee is at the point about 0.25 s distant from the response beginning, and UL should be placed at the point 0.175 s. For this UL, the calculated level is almost equal to the right one (the level deviation is 0.03 dB), while UL placed at the knee results in the level deviation of 0.34 dB. This analysis shows that SPL can be determined precisely enough even from an RIR with relatively high noise floor. However, more care should be given to the setting of integration UL.

Taking into consideration both the level decrease due to the finite integration UL and the level increase due to the noise, relatively small inaccuracy in SPL determination is obtained for UL placed at $T/3$ or $T/4$ if the noise floor is not too high (not bigger than −20 or −15 dB). For example, UL at $T/3$ and $T/4$ results in level deviations of −0.04 and −0.13 dB, respectively, in RIR with noise floor of −60 dB. However, for an RIR with noise floor higher than the mentioned −20 or −15 dB, it is better to set UL at the knee. Even smaller inaccuracy (or no inaccuracy) is obtained for optimal UL placed somewhat before the knee.

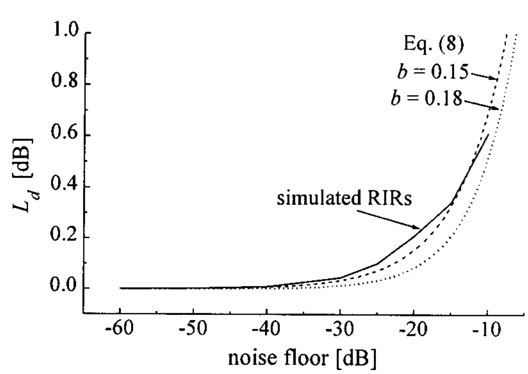


FIG. 5. The level deviations determined from simulated RIRs for the integration UL placed at the knee, and the deviations obtained by Eq. (8).

## IV. INACCURACIES OF SPL DETERMINATION IN MEASURED RIRS

In order to perform the mentioned investigations on measured RIRs, the measurements were carried out in one of the Laboratories at the Faculty of Electronic Engineering in Niš, which is similar to a classroom.[3,9] The simple PC based measurement system[3] developed at the Laboratory of Acoustics at this Faculty was used for the measurements of a number of RIRs in several points, by implementation of an MLS technique. Various noise floors in RIRs were obtained using various excitation signal levels. The RIRs with the same noise floor measured in various points lead to the similar results for the investigations performed. So, only the results obtained from RIRs measured in one point are presented in this section.

As in previous investigations, the calculated steady-state mean-square pressures are normalized by the corresponding pressure. It is calculated from the measured RIR with noise floor of about −50 dB, that is, with SNR of about 50 dB, in such a way that the integration UL is set at the knee. In order to compare in an easier way the results obtained from measured RIRs with those obtained from simulated responses, the values of UL are normalized here by the reverberation time of the laboratory, determined from broadband RIR (0.8 s). This time is approximately equal to the reverberation times at middle frequencies. The level deviations due to finite UL and noise in measured responses, shown in Fig. 6(a), are similar to those obtained in simulated responses with the same noise floor, The small differences between the corresponding deviations are presented in Fig. 6(b).

The knee of the RIR with noise floor of −10 dB is placed at the point about 0.145 s distant from the response beginning and the integration UL at the knee leads to the calculated level higher than the right one by about 0.7 dB. If the conclusions of the previous section are implemented, UL

TABLE I. The integration ULs leading to the right SPL ($L_d = 0$ dB) in simulated RIRs with various noise floors.

| Noise floor [dB] | Knee [s] | UL [s] leading to $L_d = 0$ dB | UL/knee |
|---|---|---|---|
| −5 | 0.083 | 0.082 | 0.99 |
| −10 | 0.167 | 0.126 | 0.75 |
| −15 | 0.250 | 0.171 | 0.68 |
| −20 | 0.333 | 0.233 | 0.70 |
| −25 | 0.417 | 0.281 | 0.67 |
| −30 | 0.500 | 0.331 | 0.66 |
| −40 | 0.667 | 0.439 | 0.66 |
| −50 | 0.833 | 0.552 | 0.66 |

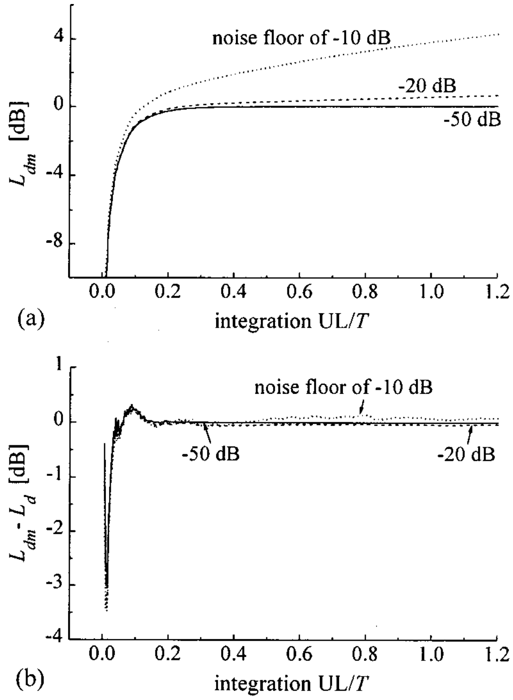


FIG. 6. The level deviations determined from measured RIRs with various noise floors ($L_{dm}$) (a) and the differences of these deviations and those determined from simulated RIRs ($L_d$) (b).

should be placed at the point obtained by multiplication of the time value of the knee by 0.7, that is, at the point 0.102 s. The integration over RIR up to this point results in the level deviation of about 0.07 dB. So, smaller deviation again appears if the UL is not placed at the knee, but somewhat before the knee.

## V. NUMBER OF AVERAGES LEADING TO DEFINED LEVEL DEVIATION

Sometimes, even in MLS technique, the excitation signal level is too low in comparison to noise level (as can be found in the measurement of sound insulation). It can even happen that the RIR comprises only the noise. In such a case, averaging increases response SNR, that is, enabling the extraction of an appropriate RIR. Obtaining an adequate number of averages to reach a defined level deviation in SPL determination from the averaged RIR is presented in this section. An empirical formula for the estimation of the required number of averages ($N$) yielding the RIR from which SPL is determined with defined level deviation has already been derived in Ref. 4

$$N=[3.12e^{-bSNR_{BA}}/L_d]^{1.23}. \tag{7}$$

The constant $b$ is equal to 0.18, while $SNR_{BA}$ represents the broadband A-weighted SNR of response before averaging.

Now, the level deviations can be calculated from the preceding equation for each SNR and for $N=1$, that is, without the averaging because of which the index $BA$ of $SNR$ is omitted

$$L_d=3.12e^{-bSNR}. \tag{8}$$

These deviations are similar to the deviations determined from simulated RIRs with the integration UL placed at the

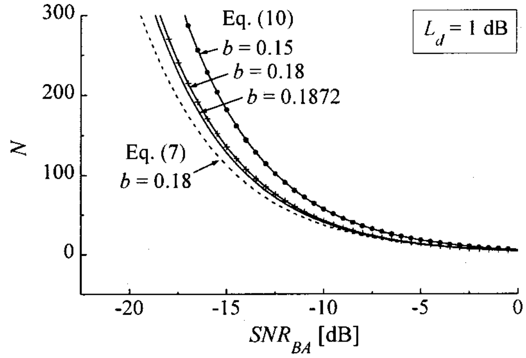


FIG. 7. The required number of averages leading to defined level deviation for UL placed at the knee calculated by Eq. (7) and by Eq. (10).

knee. The presentation of this is given in Fig. 5 using the previously described relationship that the absolute value of noise floor is approximately equal to SNR. Better agreement is obtained for $b=0.15$ in Eq. (8).

RIRs with the same SNR should lead to the same level deviation for the same integration UL, independent of the number of averages used to obtain them. So, Eq. (7) should result in such values of $N$ for various $SNR_{BA}$'s and the same $L_d$, which lead to averaged responses with the same SNR. This can be obtained if the constant $b$ gets the value of 0.1872 postulating that every doubling the number of averages results in improvement of SNR by 3 dB.

Another formula for calculation of the required number of averages yielding the defined level deviation for integration UL placed at the knee is derived here. Namely, the required SNR of response leading to the defined level deviation can be obtained based on Eq. (8). The difference between this SNR and SNR existing before averaging ($SNR_{BA}$) should be equal to the improvement of SNR obtained by averaging

$$\frac{1}{b}\ln\frac{3.12}{L_d}-SNR_{BA}=10\log N. \tag{9}$$

Solving the previous equation gives the required number of averages

$$N=10^{(1/10)((1/b)\ln(3.12/L_d)-SNR_{BA})}. \tag{10}$$

Unlike Eq. (7), this formula can be implemented for various constants $b$. Taking particular $b$, for various $SNR_{BA}$'s and the same $L_d$, it results in values of $N$, such that the averaged RIRs have the same SNR. Although Eq. (7) and Eq. (10) are different at the first sight, they result in the same $N$ for $b=0.1872$. However, for other values of $b$, the numbers of averages obtained by these equations are different. As shown in Fig. 7, the influence of $b$ on calculated number of averages is significant.

If SNR of response ($SNR_{BA}$) is too low (below 0 dB or 5 dB) for determination of right SPL using the optimal UL, the required number of averages enabling such determination is simply calculated from the required improvement of SNR obtained by averaging. Namely, the particular SNR of the response, which can be high enough for reliable determination of right SPL using optimal UL (for example, 8 dB or 10 dB), is defined as final SNR. The difference between this

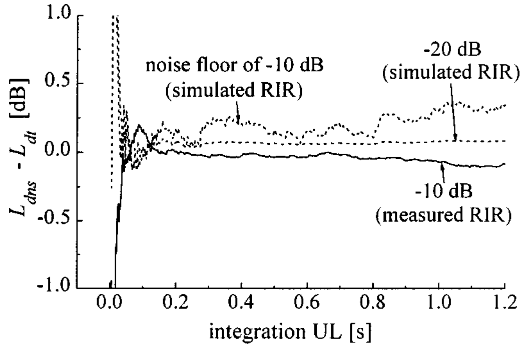


FIG. 8. The differences of the level deviations determined from the simulated and measured RIRs with various noise floors using noise subtraction ($L_{dns}$) and that one calculated by Eq. (4) (UL is normalized by $T$ for measured response).

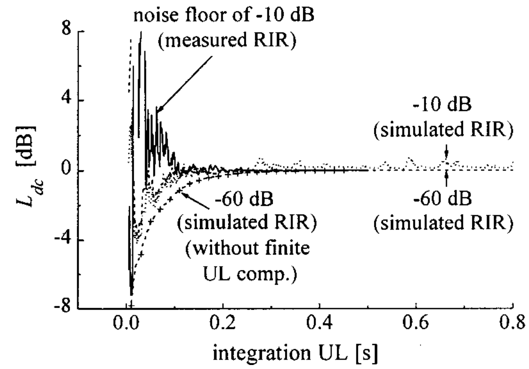


FIG. 9. The level deviations determined from simulated and measured RIRs with various noise floors implementing both noise subtraction and finite UL compensation ($L_{dc}$) (UL is normalized by $T$ for measured response).

SNR and initial $\mathrm{SNR}_{BA}$ should be equal to the SNR improvement obtained by averaging. This leads to the required number of averages.

## VI. NOISE SUBTRACTION AND FINITE UL COMPENSATION

As an alternative to the previously used approach of reducing the inaccuracies in SPL determination by setting appropriate UL, these inaccuracies can also be reduced by additional processing based on the implementation of two correction techniques. Namely, the inaccuracy caused by noise can be reduced by using the noise subtraction technique, while the inaccuracy caused by a finite UL can be reduced by using the technique called finite UL compensation.

The noise subtraction was previously used for increasing of the dynamic range of decay curve obtained by backward integration of RIR.[11] In this technique, the mean-square value of noise, calculated from the second part of response where the noise is dominant, is subtracted from squared RIR, before the integration. The response $h(t)$ comprising the noise can be presented by the sum of the RIR without noise $h_r(t)$ and the noise $n(t)$. If the mean-square value of noise $\overline{n^2}$ is now subtracted from the squared RIR, then the steady-state mean-square pressure is given by

$$p^2(t)=G\int_0^{\infty}\{h_r^2(\tau)+2h_r(\tau)n(\tau)+(n^2(\tau)-\overline{n^2})\}d\tau. \tag{11}$$

The second term in this equation $(2h_r(\tau)n(\tau))$ integrates to zero, as the noise can be either positive or negative.[11] The contribution of squared noise, that is, of noise energy, which is added to the energy of reverberant sound, is now reduced by subtraction of the mean-square value of the noise.

The investigations of implementation of this technique were performed on both simulated and measured RIRs. The obtained level deviations show that it represents an efficient technique for the reducing of inaccuracy of SPL determination due to noise. Namely, the earlier obtained level increase as a consequence of noise, now almost disappears. So, the deviations determined from the RIRs with various noise floors are similar. In this way, the differences between these deviations and the deviation calculated by Eq. (4) are considerably reduced, as shown in Fig. 8. Their values become close to zero, except for the described setting of UL close to the response beginning. It is worth mentioning that the noise subtraction technique is sensitive to accuracy of calculation of noise mean-square value. Thus, the reduction in influence of noise is dependent on this accuracy.

On the other hand, the consequence of finite integration UL in SPL determination leading to the inaccuracy is that the part of response energy from UL up to infinity is not included in the calculation. The loss of this part of energy can be offset by adding compensation energy to the energy calculated in the range from zero up to the UL. Multiplying the exponential decay term from Eq. (2) by the coefficient $B$ representing the energy density at the zero point, the general expression for squared RIR without random processes and noise becomes $Be^{-kt/T}$. The compensation energy can be now calculated by

$$E_c=B\int_{t_{ul}}^{\infty}e^{-k\tau/T}\,d\tau=B\frac{T}{k}e^{-kt_{ul}/T}=-\frac{B}{A}e^{At_{ul}}, \tag{12}$$

where $A$ is coefficient given by $A=\ln(D/B)/t_{ul}$, and $D$ is the energy density at $t_{ul}$ known as the mean noise energy density. The term energy density used for $B$ and $D$ means "temporal density, which is calculated by integrating over short time intervals."[2] In practice, the fluctuations of RIR can cause inaccuracy of the compensation energy calculation, so that this energy differs from the true loss.

In order to use RIR as long as possible for investigations of implementation of finite UL compensation, first the noise subtraction is implemented, and then finite UL compensation. In this way, correct implementations of these techniques should theoretically lead to level deviations equal to zero. However, when the integration UL is placed too close to the response beginning (up to 0.1 s from the beginning), the compensation energy is calculated with significant inaccuracy. This inaccuracy and the mentioned increased influence of fluctuations due to the smaller integration range cause level deviations that significantly vary from zero for UL placed close to the response beginning, as shown in Fig. 9. If the UL is placed far enough from the response beginning (after 0.1 s), the inaccuracy of compensation energy calculation is smaller and the level deviations tend to be approximately equal to zero. Beside being dependent on the UL, the accuracy of compensation energy calculation is dependent on the time range used for calculation of coefficients $B$ and $D$ as well. This range should not be too small due to the influence of response fluctuations, but it should also not be too big due to the decay of RIR energy.

## VII. CONCLUSIONS

The integration over squared room impulse response (RIR) up to a finite upper limit (UL) in SPL determination leads to deviation of the calculated level from the right value. The investigations of the influences of both finite UL and noise performed here show that if the appropriate point of the response is set as UL, the level deviation is acceptably small. This appropriate point can be $T/3$ or $T/4$ for RIRs with sufficiently small noise floors—smaller than $-20$ or $-15$ dB. For RIRs with higher noise floors, it is better to displace UL toward the response beginning. The reason for this is that the calculated level can be considerably higher than the right level if the UL is placed at the part of response where the noise is dominant.

One general solution for UL setting, which can be implemented in RIRs with various noise floors, is to place the UL at the knee. This UL leads to relatively small level deviation, typically less than a decibel. However, for even smaller level deviation (tending toward zero), the integration UL should be placed at the point somewhat before the knee called the optimal UL. It is distant from the RIR beginning by a constant fraction of the interval to the knee. The investigations have shown that this constant should take the value of about 0.7 for RIRs with exponential decays. By implementation of the mentioned conclusions, SPL can be determined precisely enough from the RIRs with various noise floors, even with relatively high noise floors.

Another approach in reducing or even eliminating the influences of noise and finite UL relates to additional processing including noise subtraction and finite UL compensation. The noise subtraction is an efficient technique, enabling significant reduction of inaccuracy in SPL determination due to the noise. With the implementation of this technique, the UL can be set even at the end of response independently of noise floor, or the above mentioned approach for UL setting in responses with small noise floors can be applied. On the other hand, finite UL compensation is rather sensitive to the place where the UL is set in the response, and on the response fluctuations. Due to this, finite UL is correctly compensated only if UL is distant enough from the response beginning (e.g., 0.1 s). Thus, more care should be given to the implementation of finite UL compensation, especially if UL is placed too close to the response beginning. Beside the investigated influences, other factors such as non-exponential decay or non-stationary noise can influence the inaccuracy in SPL determination, and they can be the subjects of further study.


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