SINE SWEEP OPTIMIZATION FOR ROOM IMPULSE RESPONSE MEASUREMENTS

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ABSTRACT

The use of sine sweeps is a robust method to measure room impulse responses. One particular advantage is that the frequency spectrum of the excitation signal can be controlled in the time domain – by changing the rate of frequency change – while keeping the amplitude of the signal virtually constant over time. The sine sweep approach is adopted in the measurement tool of the ODEON software. In this paper, a method to optimize the measurements is introduced. The spectrum of the sweep signal is modified, making use of a previously measured impulse response and its resulting Schroeder decay curve. The maximum dynamic range of the Schroeder curve is defined as the decay range. This decay range is calculated in octave bands, and its deviation from a broadband average is subtracted from the sweep spectrum magnitude. The goal of this approach is to redistribute the power across frequency bands in order to ensure a more uniform signal-to-noise ratio (SNR). The method is evaluated through experimental measurements. The proposed optimization leads to a more constant decay range across octave bands, with an improved SNR in bands with poor decay. Practical aspects including repeatability and sweep duration are discussed.

1. INTRODUCTION

The acoustic conditions of a room are commonly described by a set of objective parameters, such as reverberation times or clarity parameters, as described in the ISO 3382 standard [1]. These parameters can be derived from the room's impulse response, i.e. the pressure response at a given receiver position to an impulse at a given source position. An ideal source impulse with infinite energy at $t = 0$ is physically impossible to achieve. Therefore, various devices have been used to imitate impulse sources with finite energy during a short time interval. These include hand claps, popping of balloons and gunshots, which typically lack low frequency content and lead to a non-repeatable estimation of the room acoustic parameters [2]. An alternative is to use a loudspeaker source playing a longer signal. The impulse signal is derived through signal processing techniques, which ensure a better signal-to-noise ratio (SNR) across a broader frequency range and more consistent repeatability [3]. The maximum length sequence approach (MLS) creates a pseudo-random noise and infers the room impulse response using a circular cross-correlation, assuming the response is linear and time-invariant [4]. However, the MLS method has proven to be sensitive to distortion [5]. Another common approach is to use a sinusoidal sweep as the source signal. The frequencies are played subsequently, usually in an increasing order, and the impulse response is then obtained by deconvolution of the measured sweep response [5]. The sweep measurement method has proven advantageous in different aspects: 1) distortion components are easily discarded as they appear at negative times in the deconvolution. The separation between the distortion components and the linear part of the impulse response is even clearer if the deconvolution is performed in the time domain (linear deconvolution), as opposed to the frequency domain [6]; 2) an improved SNR, especially at low frequencies [7]; 3) the possibility to enhance the power of certain frequencies by "slowing down" the sweep in these regions, thus without increasing the level, which could cause damages to the driver(s) of the loudspeaker source [5].

With regard to the sweep design, it could be of interest to modify the sweep's spectrum, so that it compensates for the variations of the measurement equipment across frequencies, such as the non-flat spectrum of the source or the presence of background noise. This study investigates how a preliminary impulse response measurement, called pilot measurement, can be used to optimize the sweep. This is done by redistributing the sound power between the studied frequency bands in order to yield a similar SNR across bands. The SNR is assumed to follow the same trend as the decay range, which is the dynamic range of the integrated Schroeder curve, as calculated in ODEON [8].

This paper presents the methodology for optimizing the spectrum of the sweep from a pilot impulse response measurement. The method is tested through experimental room impulse measurements, under different noise conditions. The functionality has been added to ODEON v16.

2. METHODOLOGY

Overall, the synthesis of the sweep follows the method presented by Müller [5], where the sweep is designed in the frequency domain. A relation is given between the sweep's magnitude spectrum $X(f)$ and the group delay $\tau_g(f)$, which can be interpreted as the time at which the frequency f is played. A proportionality relation can be drawn between the amount of time spent between two frequencies f_1 and f_2 and the power between these frequencies,

$$\frac{\tau_g(f_2) - \tau_g(f_1)}{T} = \frac{\Pi(f_1, f_2)}{\Pi_{tot}}. \quad (1)$$

where $\Pi(f_1, f_2) = \int_{f_1}^{f_2} X(f)^2 df$, T is the sweep's length and Π_{tot} is the total power of the sweep. The sweep's spectrum is designed as proportional to $f^{\frac{s}{6}}$ (exponential sweep), where s is the slope in dB/octave. s is generally negative. A high-pass and a low-pass filter are also applied to the spectrum, according to the frequency range under study.

2.1 Sweep spectrum correction and design constraints

A method is hereby developed to modify the sweep's spectrum from an arbitrary set of correction values $L[i]$ expressed in octave bands in dB. The corrections are expressed in terms of power,

$$L[i] = 10\log_{10}\left(\frac{\Pi[i]}{\Pi_0[i]}\right), \quad (2)$$

where $\Pi_0[i]$ and $\Pi[i]$ are the initial and the corrected power in the ith octave band, respectively.

The correction is designed so that the power is only redistributed across bands, while the total power remains the same. If the sweep is corrected in N consecutive bands, we then have

$$\Pi_{tot} = \sum_{i=1}^{N} \Pi[i] = \sum_{i=1}^{N} \Pi_0[i]. \quad (3)$$

Using the definition of $L[i]$ in Eqn. (2), we obtain the following condition on the set of $L[i]$,

$$\sum_{i=1}^{N} \frac{\Pi_0[i]}{\Pi_{tot}} 10^{\frac{L[i]}{10}} = 1. \quad (4)$$

In the following we make use of *power ratios* $A[i] = \frac{\Pi_0[i]}{\Pi_{tot}}$, and we can also express Eqn. (4) in dB,

$$10\log_{10}\left(\sum_{i=1}^{N} A[i] 10^{\frac{L[i]}{10}}\right) = 0. \quad (5)$$

The power ratios $A[i]$ are entirely determined by the properties of the initial sweep. For example, for a pink sweep (slope -3 dB/octave), the power is the same in all bands, so $A[i] = \frac{1}{N}$. In practice, if an arbitrary set of correction values is entered and does not verify Eqn. (5), an offset $\delta = 10\log_{10}\left(\sum_{i=1}^{N} A[i] 10^{\frac{L[i]}{10}}\right)$ is subtracted from the whole set of corrections $L[i]$. This offset preserves the distribution of the corrections across bands while ensuring that Eqn. (5) is verified.

Another set of conditions is that the power in the octave bands should remain smaller than the total power,

$$\Pi[i] < \Pi_{tot}, \quad (6)$$

which translates to

$$L[i] < -10\log_{10}(A[i]). \quad (7)$$

Finally, we ensure that each band contains a minimum amount of power. This is expressed in terms of an arbitrary minimum duration per octave band t_m, following the proportionality relation Eqn. (1). In this study, t_m is set to 25 ms. Using the definition of $L[i]$ and the proportionality with power Eqn. (1), the following constraint is found for each octave band,

$$L[i] > 10\log_{10}\left(\frac{t_m}{T}\right) - 10\log_{10}(A[i]). \quad (8)$$

This lower bound consists of two terms; the first one indicates the minimum relative time spent in the band compared to the whole sweep, while the second one is an offset accounting for the existing power ratio in the initial sweep. The introduction of a minimum time spent per band also yields an upper bound, conveying the fact that given a time $t[i]$ spent in a band i, there should be enough remaining time for the other octave bands,

$$t[i] < T - (N-1)t_m. \quad (9)$$

In terms of power corrections, this makes the upper constraint Eqn. (7) stricter,

$$L[i] < 10\log_{10}\left(\frac{T - (N-1)t_m}{T}\right) - 10\log_{10}(A[i]), \quad (10)$$

where the temporal term is negative.

For a given set of corrections, the constraints in Eqn. (8) and Eqn. (10) can also be reformulated in terms of sweep length. For each frequency band i, we obtain two lower constraints,

$$T \geq \frac{t_m}{10^{\frac{L[i]}{10}} A[i]}; \quad (11)$$

$$T \geq \frac{(N-1)t_m}{1 - 10^{\frac{L[i]}{10}} A[i]}. \quad (12)$$

If the constraint from Eqn. (7) is respected, then the denominator of Eqn. (12) is strictly positive. These constraints indicate that larger variations across bands require a longer sweep duration.

In ODEON, the highest bound from Eqn. (11) and Eqn. (12) is displayed as a suggested sweep length to the user. If the user selects a shorter sweep duration, the corrections $L[i]$ will be truncated to respect the constraints Eqn. (8) and Eqn. (10).

2.2 Modified sweep implementation

The previous section described how a set of correction values per frequency band was created to redistribute the sweep's power across bands. This section explains how the spectrum is effectively implemented. The idea is to build a correction function of frequency $L(f)$, so that

$$X(f) = 10^{\frac{L(f)}{20}} X_0(f), \quad (13)$$

where X_0 corresponds to the original sweep magnitude spectrum and X to the modified spectrum.

Focusing on one octave band i, Eqn. (2) can be expressed in integral form,

$$\int_{f_{low}[i]}^{f_{high}[i]} X(f)^2 df = 10^{\frac{L[i]}{10}} \int_{f_{low}[i]}^{f_{high}[i]} X_0(f)^2 df, \quad (14)$$

where $f_{low}[i]$ and $f_{high}[i]$ are the frequency limits of the ith octave band.

We use the following coarse approximation,

$$\int_{f_{low}[i]}^{f_{high}[i]} X(f)^2 df \approx (f_{high}[i] - f_{low}[i]) X(f_c[i])^2, \quad (15)$$

where $f_c[i]$ is the center frequency of the ith octave band. Applying this approximation both to X and X_0, Eqn. (14) becomes

$$X(f_c[i])^2 = 10^{\frac{L[i]}{10}} X_0(f_c[i])^2, \quad (16)$$

which makes it possible to express $L[i]$ from the magnitude spectrum at the center frequencies,

$$L[i] = 20 \log_{10} \left(\frac{X(f_c[i])}{X_0(f_c[i])} \right) = L(f_c[i]). \quad (17)$$

The correction function $L(f)$ is built by cubic interpolation, which requires a number of control points across the frequency spectrum. The interpolation is carried out on a log-frequency scale, so that the octave bands are equally weighted. The first control points are situated at the center frequencies of the studied octave bands, and are assigned the value $L[i]$, following Eqn. (17). Initial tests have shown that interpolating with only these points leads to a too coarse magnitude spectrum. Therefore, additional control points are also created at the limits of the octave bands, with a value equal to the average of the corrections $L[i]$ at the previous and at the next band. Finally, the sweep is designed on a given number of octave bands, but the whole audible range must be covered to avoid unexpected artefacts outside of the studied frequency range. This is done by imposing a correction of 0 dB to all the lower bands down to 16 Hz and to all the higher bands up to 16 kHz. Note that by design the spectrum is bandpass filtered so the outside bands are already attenuated in the original spectrum. Fig. 1 illustrates the implementation of the correction function in dB (gray line), including the control points used to derive it, in an example from the experimental results in Sec. 3 (Ambient noise, Pilot 1). Once $L(f)$ is found by interpolation, the resulting corrected spectrum $X(f)$ can be found using Eqn. (13). Fig. 2 compares the initial sweep spectrum and the corrected sweep spectrum for the same example from Sec. 3.

2.3 Correction from a pilot measurement

The decay range corresponds to the dynamic range of the integrated Schroeder curve – early peak excluded. It is influenced by factors such as the loudspeaker's response, the background noise, the room's response and the sweep length. The decay range is thus an indicator of the quality of the measurements, especially when deriving the ISO 3382 parameters [9]. For instance, it is established that the derivation of the T_{20} parameter requires a decay range of at least 35 dB [1].

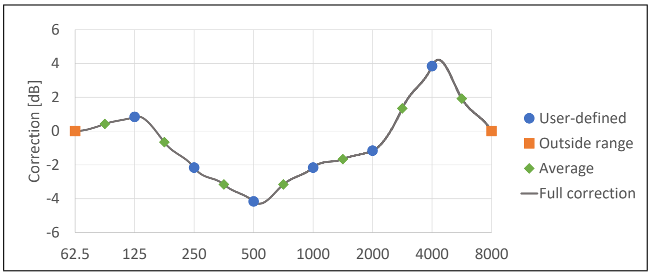

Figure 1. Interpolation of the correction function from control points. Data from the case Ambient noise, Pilot 1 (see Sec. 3).

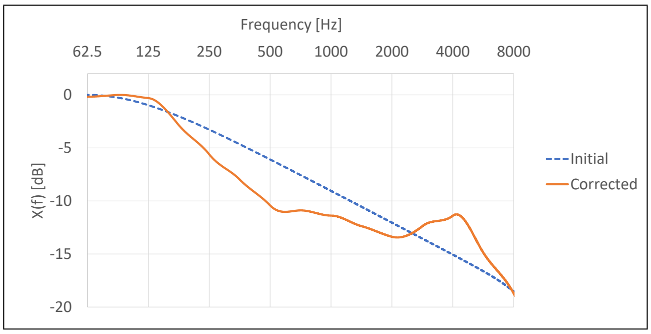

Figure 2. Comparison of an initial spectrum and a corrected spectrum. Data from Ambient Pilot 1 correction (see Sec. 3).

In the scope of this study, the decay range is automatically calculated in octave bands by ODEON, and it can serve as an indication of the frequency distribution of the SNR. The proposed methodology consists of redistributing the sweep's power to obtain the same SNR at all frequency bands. An initial pilot measurement is performed to estimate the decay range, which is used to correct the sweep's spectrum. The measurement is then repeated with the corrected sweep in the exact same experimental conditions. On top of the assumption of stationarity, we assume that the process is linear, so a 1 dB correction in the spectrum would lead to a 1 dB correction in decay range as well.

The corrected sweep is designed to compensate for the variations of the decay range across the octave bands. Therefore the corrections $L[i]$ are initially taken as the negative of the decay range values. From these initial values, the offset explained in Eqn. (5) is applied. The automatically calculated corrections are finally truncated to fulfill the power constraints Eqn. (8) and Eqn. (10), for the sweep length indicated by the user.

3. EXPERIMENTAL RESULTS

3.1 Setup

Impulse response measurements were performed in a room shown in Fig. 3, using an omnidirectional dodecahedron speaker and an omnidirectional microphone. Both the source and the receiver were kept at the same position for all measurements. The sine sweeps were designed from 125 Hz to 4 kHz, which is the frequency range recommended in [1], with a slope of -3 dB/octave (pink sweep) and a length of 8 s.

Figure 3. Measurement setup in a meeting room. Room dimensions 5 m $\times$ 9.3 m $\times$ 2.9 m.

3.2 Study of the background noises

The measurements were performed in two different noise conditions: in ambient conditions and with an active hoover in the room. In both cases, various intermittent sounds (e.g. ventilation, passing vehicles outside) contributed to some instability in the background noise. First, the background noise was measured several times with a sound level meter and averaged to reduce the effect of intermittent noise sources. Fig. 4 shows the measured average background noise L_{eq} in the two conditions. As expected, the noise levels are lower in the ambient conditions, and they decrease with frequency – from 37 dB at 125 Hz to 15 dB at 4 kHz. The hoover conditions result in higher sound pressure levels, from 47 dB at 125 Hz and with a 60 dB peak at 1 kHz.

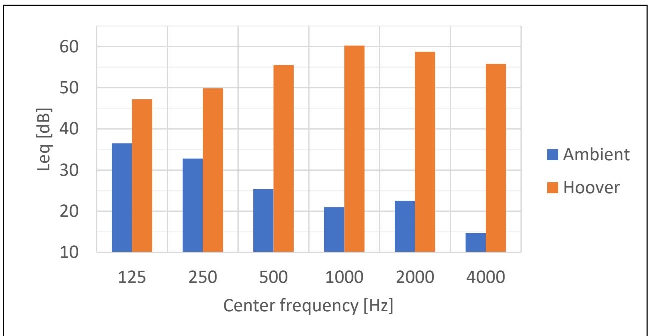

Figure 4. Average of measured background noise in ambient and in hoover conditions.

Fig. 5 shows the measured decay range per band for two pilot measurements of 8 s in each measurement condition. The decay ranges reflect well the measured background noise in Fig. 4: the ambient conditions lead to overall higher values due to the lower noise floor, and the decay ranges in hoover conditions decrease with frequency up to 1 kHz. Furthermore, the ambient conditions show an already quite flat decay range across frequencies, with values between 55 dB and 63 dB. However, in the hoover conditions, the decay range values span from 23 dB to 48 dB. In terms of repeatability, the two measured pilots in ambient conditions yield similar values, except at 500 Hz where they differ by 4 dB. In the hoover case, the general shape across bands is respected but differences up to 3 dB between the two pilots are visible at 125 Hz, 1 kHz and 2 kHz. This can be explained by the variations in the background noise during the measurements, as mentioned before. These results illustrate that a proper measurement of the decay range depends on the stationarity of the background noise. If it is not stationary, then the measured decay range may vary in time and the correction might eventually fail.

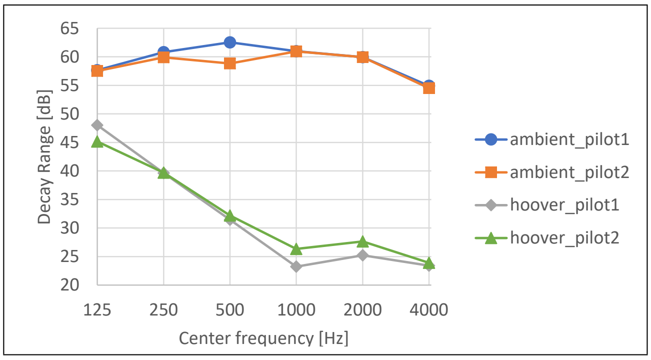

Figure 5. Measured decay range for pilot measurements of 8 s in ambient and hoover conditions.

Tab. 1 contains the corrections obtained from the measured pilot decay ranges of Fig. 5, following the method presented in Sec. 2.3. In ambient conditions, as the measured decay ranges were so similar, both pilots lead to almost identical corrections, with a largest difference of 3 dB at 500 Hz. In this case, the effect of the correction is mainly to boost the 4 kHz band by removing power in the mid-frequencies. In hoover conditions, the two pilots lead again to similar corrections. The correction consists of attenuating the low frequencies (125 Hz-500 Hz) to boost the high frequencies. It can be noted that the large reduction in the bands 125 Hz and 250 Hz only allow for an increase of up to 4 dB in the higher frequencies, due to the logarithmic nature of the dB scale. Furthermore, the amount of variations calculated for the first pilot is not achievable for a sweep of 8 s to respect Eqn. (8). Therefore the -20 dB correction at 125 Hz is truncated to -17 dB in practice. If the full correction is desired, the sweep duration should be increased. In that regard, ODEON allows sweep durations up to 80 s, which would increase the sweep's power by an additional 10 dB.

3.3 Results after correction

For each pilot presented in Sec. 3.2, three corrected sweeps were measured. This section compares the decay ranges of the corrected sweeps with their respective pilots. Their

f [Hz]	125	250	500	1000	2000	4000
ambient_pilot1	1	-2	-4	-2	-1	4
ambient_pilot2	1	-2	-1	-3	-2	4
hoover_pilot1	-20	-13	-5	3	2	4
hoover_pilot2	-17	-12	-4	2	0	4

Table 1. Sweep spectrum corrections calculated from pilot decay ranges per octave band.

flatness is measured in terms of standard deviation across the frequency bands from 125 Hz to 4 kHz. Only one pilot in each noise condition is presented in detail.

The decay ranges measured for the corrections from Pilot 1 in ambient conditions are presented per octave band in Fig. 6. The decay range from Pilot 1 is also plotted for reference as a dashed line. While the three corrected measurements should be identical, their decay ranges differ at low frequencies, by up to 4 dB at 250 Hz. This could be due to the variations in the background noise during the measurements. Nevertheless, from 1 kHz, the three corrected sweeps lead to a similar decay range of about 58 dB. Both the expected reduction of the mid-frequencies and the boost at 4 kHz are apparent for the three corrected sweeps. Therefore, the correction is particularly successful above 1 kHz, both in terms of repeatability and flatness of the decay range across bands. The corrections from Pilot 2 – not shown in this paper – also show more variability below 1 kHz and more consistent and flatter decay ranges at higher frequencies. The standard deviations of the decay ranges are reported for the two pilots and their respective corrections in Tab. 2. The two pilots have similar standard deviations, because of their similar decay ranges (see Fig. 5). The three corrections from Pilot 1 yield a smaller standard deviation, particularly due to the flat decay ranges observed at high frequencies in Fig. 6 and a relatively effective correction of the lower frequency bands. The higher standard deviation for Correction 3 is explained by its large decay range variations at 250 Hz and 500 Hz. The improvement in standard deviation is not as clear for the corrections from Pilot 2, especially because they tend to increase the decay range at 125 Hz and 250 Hz (not shown in the paper). These results show that the corrected sweeps can lead to different outcomes, depending on the quality of the pilot measurement and the consistency of the measurement conditions.

Sweep measurement	Standard deviation
Pilot 1	2.51
Pilot 1 - Correction 1	0.97
Pilot 1 - Correction 2	1.09
Pilot 1 - Correction 3	2.04
Pilot 2	2.12
Pilot 2 - Correction 1	1.27
Pilot 2 - Correction 2	4.22
Pilot 2 - Correction 3	2.12

Table 2. Standard deviation of the decay range for the two pilots and their corrections. Ambient conditions.

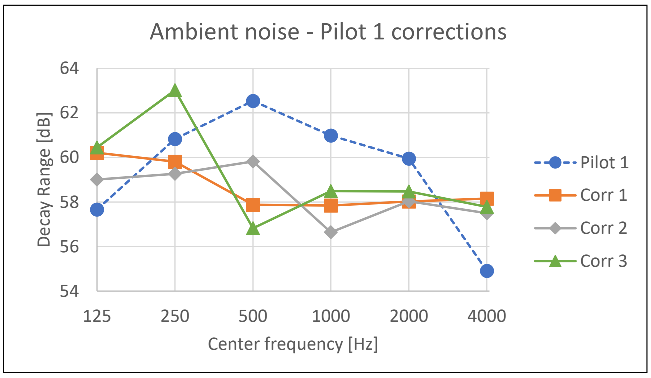

Figure 6. Measured decay range per octave band for sweeps corrected from Pilot 1 in ambient conditions.

The same comparison is carried out in hoover-operating conditions. Fig. 7 reports the decay ranges per octave band for the three measurements corrected from Pilot 1, plotted with the pilot decay range as a dashed line. Overall, we obtain similar decay ranges with the three corrected sweeps, with more variability at lower frequencies. The decay range is reduced in the bands below 500 Hz and increased above 1 kHz. At 125 Hz, the correction is truncated due to the too short sweep duration, which explains why the decay range is still higher than in the other bands. The 250 Hz band also shows a still high decay range, while the 500 Hz band has much lower values (below 25 dB). This could be due to the variations in the background noise, but it is also possible that the corrections between neighboring bands influence each other, especially when the approximation Eqn. (15) is not valid. From 1 kHz upwards, all three measurements lead to a flat decay range of about 26 dB. The measurements corrected from Pilot 2 are not shown in the paper, but they lead to similar results as Pilot 1, with a flat decay range from 1 kHz and variations in the lower frequencies. Tab. 3 reports the standard deviations in decay range for the two pilots and their respective corrections. The standard deviations of the pilot measurements are much higher than in the ambient conditions, due to the larger range of values observed in Fig. 5. For Pilot 1, Fig. 7 showed that the corrected decay ranges were flatter, which is also seen in the standard deviations, dropping to about 3 dB. The difference between the three corrections is mostly due to an inconsistent decay range estimation at 125 Hz. The corrections from Pilot 2 also lead to a substantial decrease in the standard deviation. The standard deviations are actually smaller than the corrections from Pilot 1 because the spectrum corrections were not truncated at 125 Hz. Overall, the decrease of the standard deviation shows that the correction was rather effective in hoover noise conditions. However, the resulting decay range is still not as flat as in ambient conditions, as the lower frequencies have a relatively higher decay range than the higher frequencies. It is possible that the method cannot correct for such a large span of decay range values (25 dB).

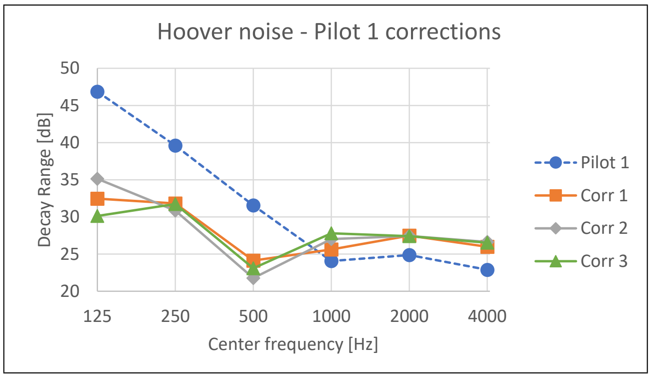

Figure 7. Measured decay range for sweeps corrected from the first pilot in hoover conditions.

Sweep measurement	Standard deviation
Pilot 1	8.90
Pilot 1 - Correction 1	3.14
Pilot 1 - Correction 2	4.10
Pilot 1 - Correction 2	2.74
Pilot 2	7.70
Pilot 2 - Correction 1	2.30
Pilot 2 - Correction 2	3.00
Pilot 1 - Correction 2	2.85

Table 3. Standard deviation of the decay range for the two pilots and their corrections. Hoover conditions.

3.4 Influence of sweep length

In the previous section, the corrections in hoover conditions required large power variations between octave bands, which can be achieved with longer sweeps. In this section, the corrections are applied for different sweep lengths (8 s, 16 s, 32 s). For each sweep length, three measurements are performed and the resulting decay ranges are averaged, in order to reduce the uncertainty observed in the previous measurements.

Fig. 8 shows the average decay range for sweeps of different durations corrected from Pilot 1, together with the measured decay range of Pilot 1 as a dashed line. In accordance with Sec. 3.3, the 8 s sweep leads to a relative attenuation of the low frequencies, and increased decay ranges at high frequencies. The 16 s sweeps lead to an overall increase of the decay range of about 4 dB which is particularly visible above 250 Hz. A 3 dB increase in SNR is indeed expected for a doubling of the sweep duration [10]. At 125 Hz and 250 Hz, the decay range is very similar to

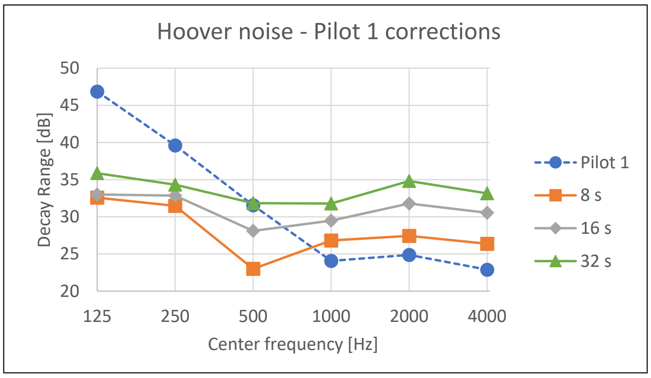

Figure 8. Decay range of corrected sweep measurements with different sweep lengths in hoover noise conditions.

the 8 s case, probably because the correction at 125 Hz is no longer truncated (-20 dB). This results in a flatter decay range curve than the 8 s sweep. The 32 s case shows another decay range increase of about 3 dB over the whole spectrum.

The influence of sweep length is also manifest when studying the standard deviations in Tab. 4: the 8 s correction already reduces the deviation by almost 6 dB, but using longer sweep reduces it even further, to less than 2 dB. Such standard deviation values are now comparable to the results obtained in ambient conditions.

Sweep measurement	Standard deviation
Pilot 1	8.90
8 s	3.22
16 s	1.78
32 s	1.51

Table 4. Standard deviation of the decay ranges for different sweep lengths in hoover conditions.

These examples illustrate that longer sweeps lead to an overall increase of the decay range, and that they also allow for more power variations across bands. It is then easier to obtain a flat decay range, which is the design goal of the present sweep correction.

3.5 Target decay range

The data from Fig. 8 can also be represented as the difference in decay range between the corrected sweep and the pilot. This difference is plotted in Fig. 9 for the three sweep lengths in hoover noise conditions. The graph also shows the spectrum corrections $L[i]$ for Pilot 1, as specified in Tab. 1. The increase of 3 dB per doubling of sweep length is visible, particularly at high frequencies. Moreover, the graph indicates that the spectrum correction and the resulting deviation in decay range from the pilot follow the same trend. For the 8 s sweep, the deviation actually coincides with the correction above 1 kHz.

One consequence of Fig. 9 is that one can predict the obtained decay range if the correction is fully effective. This flat decay range value D_f should theoretically be the

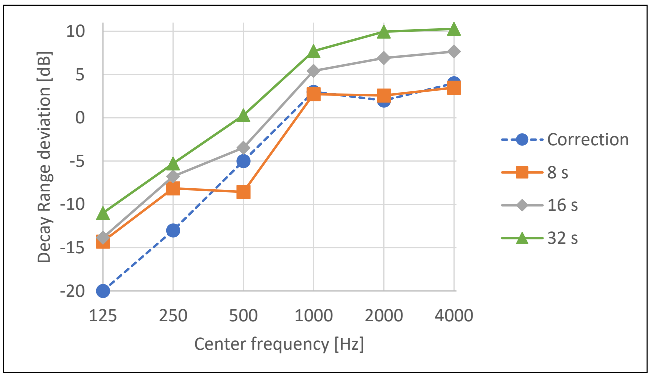

Figure 9. Decay range deviation from Pilot 1 for different sweep lengths in hoover noise conditions.

same in all bands and it corresponds to the offset calculated in Sec. 2.1,

$$D_f = -10\log_{10}\left(\sum_{i=1}^{N} A[i]10^{\frac{-D[i]}{10}}\right), \tag{18}$$

where $D[i]$ is the measured decay range in the ith frequency band. As an illustration, Tab. 5 shows the D_f values for the 8 s sweeps presented in Sec. 3.2. In ambient conditions, Fig. 6 shows that the corrected sweeps have indeed a flat decay range of about 58 dB at high frequencies. In the same way, the corrected sweeps in Fig. 7 have a decay range around 26 dB at high frequencies. These values are hence consistent with Tab. 5.

Sweep measurement	$\mathrm{D_f}$ [dB]
Ambient Pilot 1	58.7
Ambient Pilot 2	58.0
Hoover Pilot 1	26.6
Hoover Pilot 2	27.8

Table 5. Flat decay range values for the four measured pilots.

It is already known that the decay range varies logarithmically with the sweep length [10]. This makes it possible to find a recommended sweep length, which ensures a target value D_t for the flat decay range. If the pilot measurement has a duration T_0 and a flat decay range value D_{f0}, the suggested sweep length T_1 is

$$T_1 = T_0 \times 10^{\frac{D_t - D_{f0}}{10}}. \tag{19}$$

Adjusting the sweep length may be useful if one wants to achieve a given minimum decay range at all bands. This is a prerequisite to derive room acoustic parameters such as reverberation time. For instance, the standards indicate a minimum decay range of 35 dB to derive the T_{20} parameter [1]. ODEON makes use of a truncation method, which makes it possible to derive T_{20} down to 25 dB [10]. If we choose a target value of 30 dB to account for uncertainties in the decay range estimation, the suggested sweep lengths for the two pilots in hoover conditions are respectively 17.5 s and 13.2 s. These rough estimates show that 16 s sweeps should be sufficient to obtain 25 dB decay range in all bands and derive T_{20}, which corroborates with Fig. 8.

4. DISCUSSION

The experimental results show that the proposed optimization method works in principle, as power is effectively redistributed towards the bands with a lower decay range.

The optimization method relies on the assumption that the pilot sweep and the corrected sweep are measured under the same stationary conditions. A particularly important aspect is the estimation of the measured pilot decay range, and more precisely its variations across octave bands. In principle, these variations are characteristic of the measurement conditions. However, the experimental results of Sec. 3 showed that the same measurement conditions do not always lead to the same measured decay range, partly because the background noise is not entirely stationary. The estimation of the decay range is especially sensitive at low frequencies, because the room no longer follows an exponential decay and the octave-band filtering of the impulse response introduces lobes. Longer sweep durations could improve the estimation of the pilot decay range, as they ensure a higher SNR. However, background noise is more susceptible to change over a longer period of time.

The measured decay range is an indicator of the quality of the measurements, but it also conditions the derivation of room acoustic parameters. For instance, the decay range should be above 25 dB to derive T_{20} in ODEON. In the measurements of Sec. 3 in hoover conditions, the pilot decay range is below 25 dB for frequencies above 1 kHz, as seen in Fig. 7. Of course, increasing the sweep length increases the decay range over the whole spectrum. However, the proposed correction optimizes the measurements for a given sweep length. As an illustration, Tab. 6 shows the decay range and the T_{20} derived from Pilot 1 in hoover conditions and from its three corrected sweeps. The decay range at 1 kHz, 2 kHz and 4 kHz is increased for the three corrections and reaches values above 25 dB, which makes it possible to estimate T_{20}. The resulting T_{20} values are consistent, except for Correction 1 at 1 kHz, where the decay range is still too close to 25 dB. At 125 Hz and 250 Hz, the decay range in the corrected measurements is considerably decreased but it is still well above 25 dB. Therefore, the estimated T_{20} values are not too affected by the correction. The 500 Hz band is problematic because of the too large attenuation of the corrected sweeps: the corrected decay ranges are below 25 dB while it was not the case for the pilot. Overall, the corrected sweeps still show an improvement as they can determine T_{20} on 5 out of the 6 octave bands, versus 3 out of 6 bands for the pilot.

The spectrum correction only ensures a flat decay range across frequencies, by redistributing the available power between the octave bands. If there is too little energy in the sweep, it is not guaranteed that the bands which had sufficient decay range will still have enough power in the corrected measurements, as seen at 500 Hz in Tab. 6. There-

f [Hz]	125	250	500	1000	2000	4000
Decay range [dB]						
Pilot 1	46.9	39.6	31.6	**24.1**	**24.9**	**22.9**
Correction 1	32.5	31.8	**24.1**	25.6	27.5	26.0
Correction 2	35.1	30.9	**21.8**	27.0	27.4	26.6
Correction 3	30.1	31.7	**23.1**	27.8	27.4	26.5
T_{20} [s]						
Pilot 1	0.62	0.68	0.68	***	***	***
Correction 1	0.64	0.64	***	0.61	0.56	0.56
Correction 2	0.62	0.69	***	0.56	0.55	0.54
Correction 3	0.59	0.67	***	0.55	0.56	0.54

Table 6. Measured decay range and T_{20} for a pilot sweep and two corrected sweeps of 8 s in hoover conditions. Decay range values below 25 dB (shown in bold red) are not sufficient for calculating T_{20}.

fore, adjusting the sweep length as described in Sec. 3.5 is also essential to ensure sufficient decay range in every band.

5. CONCLUSION

This study presents a method to optimize room impulse response measurements with a sine sweep. The sweep's spectrum is modified to account for frequency variations of the SNR. The SNR variations are estimated using the measured decay range by a pilot sweep. This results in a corrected sweep with varying speed and almost constant amplitude, which should yield a flatter decay range across octave bands.

Experimental tests show conclusive results at high frequencies, where a flat and repeatable decay range is obtained. Nevertheless, the method requires stationary conditions during the impulse response measurements, especially in terms of background noise. In addition, the optimization depends on the accuracy of the estimated decay range, which is more sensitive at lower frequencies. The amount of corrections is limited by the sweep's properties, including its magnitude spectrum and its duration. Finally, the optimization yields a flatter decay range, but in many cases the sweep length should still be adjusted to guarantee a sufficient SNR in all bands. This is nevertheless achievable with shorter durations than with uncorrected sweeps.

Although the analysis focused on correcting for the background noise, this sweep optimization method can also correct for any other aspect of the measurement chain, such as the source's spectrum. Further improvement could be made by also changing the sweep's amplitude to allow for more variations across octave bands.

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