Background Noise Effects Reduction in Swept Sine Measurements of a Room Impulse Response

Dejan Ćirić [1], Marko Janković [2] and Aleksandar Pantić [3]

Abstract – **Main disturbances in acoustic measurements come from noise and distortion limiting the accuracy and reliability. This is also valid for the room impulse response measurements carried out even by the sophisticated techniques such as swept sine. In order to reduce the negative effects of background noise, a method based on known spectrum of the excitation swept sine is developed and analysed in this paper. Applying this method, it is possible to significantly reduce noise in the non-causal part of the impulse response, but also the noise effects in the causal part can be reduced. In this way, the impulse response dynamic range can be increased.**

Keywords – **Noise, Swept sine measurements, Room impulse response, Dynamic range.**

I. Introduction

Acoustic measurements are an important tool for acoustic investigations, analysis of acoustical problems or for creation of experimental references in theoretical and numerical approaches [1]. The measurements of a tested system Impulse Response (IR) has a very specific position in acoustics, and in some cases, such as in room acoustics, play a crucial role. The IR describes the linear transmission properties of a system able to transport or transform energy in a certain frequency range [2]. The accuracy of IR measurements is limited by the instrumentation, but also by the disturbances among which distortion and noise stand out [3].

The influence of noise is basically related to its interference with useful signal [4] reducing the dynamic range of the measured response. This negative effect depends to a certain extent on the technique applied for the measurement. There are some alternatives that can be applied during the measurements in order to reduce the noise effects. Another option is to apply an adequate post-processing method.

This paper focuses on a specific post-processing method developed for reducing the noise effects in the room IR measurements by the swept sine technique [2,5]. It is based on the fact that the excitation signal is deterministic and that the spectral content of its time segments of short enough duration is narrowband. The developed method can be applied to both transient and background noise, although only the latter one is considered here. A special attention is paid to the consequences of the noise effects reduction and influence of some parameters of the developed method to its efficiency.

[1]Dejan Ćirić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: dejan.ciric@elfak.ni.ac.rs.

[2]Marko Janković is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: marestudio2004@gmail.com.

[3]Aleksandar Pantić is with the Knauf Insulation d.o.o Belgrade, Industrijsko naselje Belo polje bb, 17530 Surdulica, Serbia, , E-mail: aleksandar.pantic@knaufinsulation.com.

II. Noise effects in room impulse response measurements

Noise is present in almost all environments, and as such, it is an inherent part of any acoustic measurement. Two most important types of noise relevant for the acoustic measurements are background (ambient) and transient noise. Background noise can be defined as overall noise present in an ambient where the measurements are done. It is actually noise (airborne, structure-borne and instrument noise) generated by all sources not related to a particular sound that is of interest.

The main consequence of noise during a room IR measurement is a decrease in IR dynamic range, that is, Signal-to-Noise Ratio (SNR). This negative noise effect could be generally reduced by increasing the excitation signal level. Unfortunately, this will also increase the distortion that could again reduce the dynamic range in some measurement techniques [2]. Another possibility for increasing the dynamic range (SNR) is the averaging of multiple responses measured under the same conditions. It is well known that the level of uncorrelated noise is reduced by 3 dB by every doubling the number of averaged responses [2].

When not a room IR is considered, but the decay curve obtained by the backward integration of this IR [6], then various methods have been proposed for the noise compensation. They include the method where the period of integration is limited, the method based on subtracting an estimated noise energy level from a response or the method where room IRs from two separate measurements are multiplied before the integration [7].

The consequences of noise depend on the technique applied for a room IR measurement. In the techniques such as Maximum Length Sequence (MLS) or swept sine [2], these consequences are not that serious as in some other (e.g. single impulse method). The swept sine technique is considered to be a technique enabling high SNR [2,5].

However, the distribution of noise artifact in this technique is somehow unique. If we look at the spectrogram of an IR measured by the swept sine technique presented in Fig. 1(a), we can see a specific distribution in the time-frequency domain. When this IR is filtered in octave or third-octave bands, there is a range of approximately stationary noise artifact shifted along time axis depending on the frequency. At lower frequencies, it is shifted to the right (towards the end of the IR) (see Fig. 1(b)), and at higher frequencies it is shifted in the opposite direction (see Fig. 1(c)).

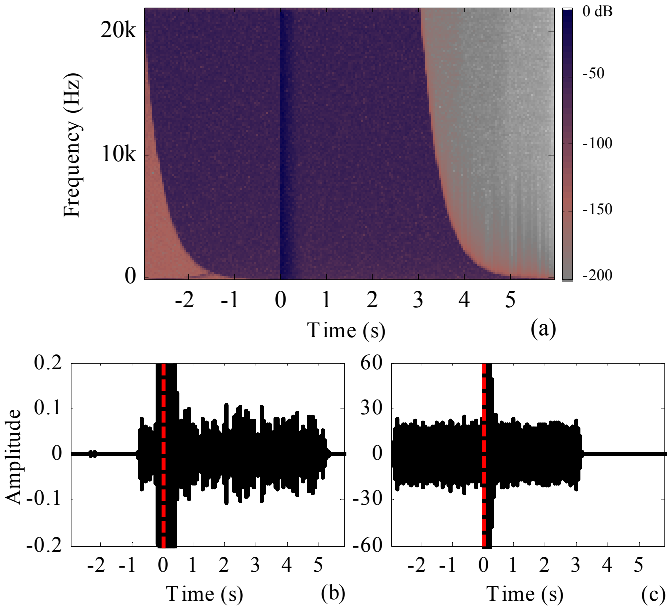

Fig. 1. Room IR with present background noise: (a) spectrogram, and zoom view of the part of IR with noise filtered in third-octave bands at (b) 100 Hz and (c) 16 kHz.

III. Method for Noise Effects Reduction

The idea based on which a method for noise effects reduction is developed here is rather simple one and can be described as follows. The excitation in the swept sine technique is a deterministic sine signal whose frequency is swept in time either linearly or exponentially [2,5]. This signal is completely known. It can be divided into shorter (time) segments. Any of these segments contains the spectral components only in a limited frequency range. There is no excitation energy outside that range. Its position on the frequency axis depends on the position and duration of the time segment. A segment closer to the swept sine beginning has a frequency range at lower frequencies. Also, a segment with longer duration has generally wider frequency range.

The excitation swept sine can be divided into segments in different ways. One of them is to create the segments of equal duration as done in Fig. 2(a). The corresponding frequency ranges of these segments will not have equal width (bandwidth) - the bandwidth at lower frequencies will be smaller than at higher frequencies (see Fig. 2(c)). Another possibility is to divide the swept sine into segments of equal bandwidth (see Fig. 2(d)). The segments obtained in such a way will have different durations (in time), as presented in Fig. 2(b). The swept sine can be divided into segments by combining two previously mentioned possibilities: some segments will have equal duration while the others will have equal bandwidth. One more alternative is to create the segments of different durations and different bandwidths.

If a room response to the excitation swept sine is divided into segments in the same way as done for the swept sine, the frequency bandwidths of the coincident segments in the swept sine and room response to this signal can be considered to be the same. Now, for evry of these segments, it would be necessary to pass (filter) the spectral components from the bandwidth of that segment, and not pass (filter out or significantly attenuate) all the components outside the bandwidth. This could be done by bandpass filtering. This feature was already applied for the transient noise removal in the swept sine measurements [8]. However, in case of background noise reduction or removal, it would require design of a number of bandpass filters with rather strict specifications that could cause certain problems. This is why a somewhat different approach (although similar to filtering) is chosen here.

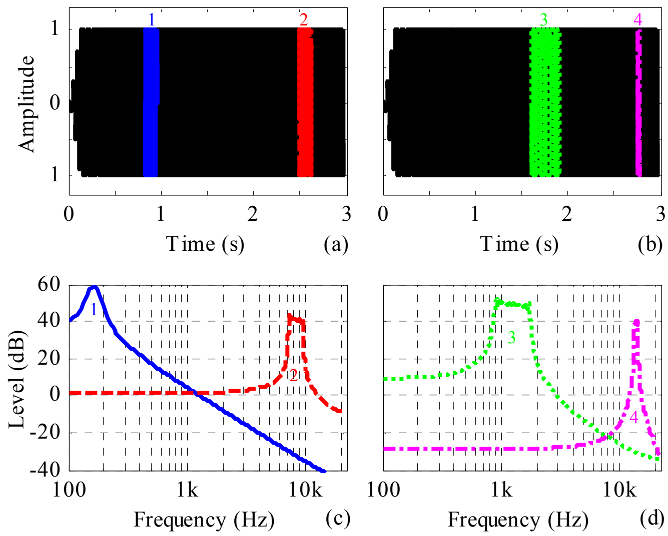

Fig. 2. The exponential swept sine divided into segments of (a) equal duration, and (b) equal frequency bandwidth, together with the spectra of these segments: (c) spectra of the segments from (a), and (d) spectra of the segments from (b).

Reduction or removal of the noise components outside the considered bandwidth (bandwidth of the particular swept sine segment) is realized in the way presented in Fig. 3. First, the excitation swept sine and response to this signal (but only up to *L* representing the length of the swept sine) are divided into segments according to one of the alternative possibilities described above. The corresponding segments in these signals are coincident in time.

These segments are then transformed to the frequency domain. The spectrum of each of the swept sine segments is first normalized to its maximum value, and then modified. This is done so that its value becomes 1 in the target bandwidth (bandwidth of the swept sine segment or somewhat wider), while the values outside this bandwidth remain unchanged. The normalized and modified spectra of the swept sine segments are multiplied by the spectra of the corresponding segments of the response to the swept sine. In this way, the corrected spectrum for each of the response segments is obtained. It should be noticed that the phase of the frequency counterparts of the response segments remain unchanged. The corrected segments from the frequency domain are then transformed back to the time domain. Summing of all corrected segments in the time domain leads to the corrected response with reduced noise.

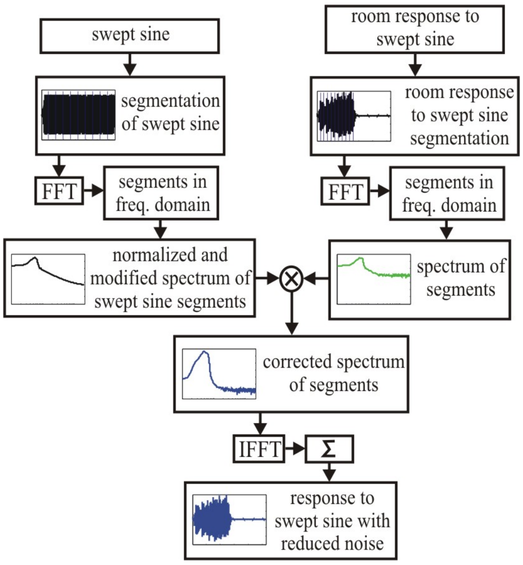

Fig. 3. Flow diagram of the developed method for background noise reduction.

IV. Results

The method for background noise effects reduction is applied here to a simulated room IR generated by the model described in [9]. The measurement procedure is simulated by using adequate equations. An exponential swept sine of length (L) equal to that one of an MLS signal of degree 17 covering the range from 20 Hz to 22.05 kHz is chosen to be an excitation signal. The sampling frequency is 44.1 kHz. Since the room IR is set to be noiseless, background noise of controlled level is added to the room response to the excitation swept sine.

The developed method is also tested on a number of measured room IRs, but due to the lack of space these results will be presented elsewhere.

The spectrogram of the extracted room IR when original (not-reduced) noise is present is already shown in Fig. 1(a). When there is no noise in the room response up to L, which is a theoretical target in a noise removal procedure, the spectrogram has a shape as in Fig. 4(a). This theoretical target can be hardly reached.

Although all previously mentioned segmentations of the swept sine and response to this signal are implemented, only the results for the third segmentation are presented here. In this segmentation, a part of the segmented signals (3/4 of the signal) is divided into segments of equal (time) duration, while the rest part is divided into segments of equal (frequency) bandwidth. The numbers of segments with equal duration and equal bandwidth are the same. The effects of some parameters of the noise reduction procedure are analysed including the width of the passband and number of segments.

The bandwidth of each segment of the swept sine (target bandwidth) can be determined as a difference between the highest and lowest frequency of that particular segment (lower and upper cutoff frequencies - f_{c_low} and f_{c_up}). In case of the exponential swept sine, these frequencies can be calculated by

$$f_{c\_low} = A_1 \cdot f_1 \cdot e^{\frac{t_{s\_start}}{T_{ss}} \cdot \ln \frac{f_2}{f_1}} \qquad f_{c\_up} = A_2 \cdot f_1 \cdot e^{\frac{t_{s\_end}}{T_{ss}} \cdot \ln \frac{f_2}{f_1}} \qquad (1)$$

where f_1 and f_2 represent the starting and ending frequency of the swept sine, T_{ss} is the swept sine duration, A_1 and A_2 are the constants shifting the cutoff frequency in a desired direction, while t_{s_start} and t_{s_end} represent the segment start and end, respectively, in time in reference to the start of the swept sine.

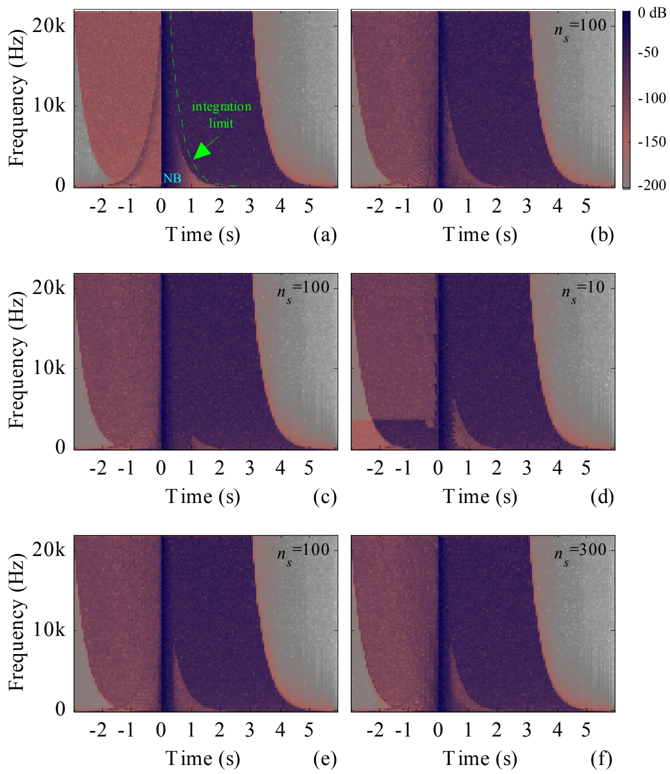

Fig. 4. Spectrograms of the room IRs extracted (a) without noise up to L, with noise reduced by the developed method using the bandwidth limits from Eq. (1) for (b) A_1=1 and A_2=1, and wider bandwidths ((c) A_1=0.1 and A_2=1.05, (d)-(f) A_1=0.42 and A_2=1.05) for the number of segments (n_s) given in the upper corner.

When the target bandwidths (applied for the described modification of swept sine spectrum) are equal to the swept sine segment bandwidths (when A_1=1 and A_2=1 in Eq. (1)), the developed method reduces noise significantly in the non-causal part of the IR (up to L, that is, 0 s). This is also the case for a part of the causal room IR (from the direct sound (L or 0 s) to the end of response), as presented by the spectrogram in Fig. 4(b). Unfortunately, at the same time, a part of the IR is also removed with noise. This can be prevented by widening the target bandwidth, that is, by setting the constant A_1 to be smaller than 1, and A_2 to be greater than 1. By increasing the constant A_2 beyond 1, the left edge of vertical noise band around the IR (denoted by NB in the spectrogram in Fig. 4(a)) is shifted to the left. In the same way, by reducing the constant A_1 below 1, the right edge of noise band is shifted to the right (see Fig. 4(c)), and this widening of the target bandwidth is of higher importance. By choosing adequate values for constants A_1 and A_2, there will be no loss of the room IR, and the reduction of noise could still be significant. This will not be the case if the target bandwidth is too narrow or too wide. The constant A_2 can take a value only slightly larger than 1, e.g. 1.05. Regarding the constant A_1, the best results (no loss of the IR and the greatest noise reduction) are obtained for an optimal value of this constant, which is in the analysed example approximately 0.42 (see Fig. 4(e)).

Regarding the number of segments (n_s), for rather small n_s, the vertical noise band in the spectrogram can have stepwise shape and noise present at lower frequencies can be larger, as presented in Fig. 4(d). On the other hand, if n_s is too large, for example, above 300 or 500 in the analysed case, there is a sort of additional noise that increases overall noise in the extracted IR (see Fig. 4(f)). This implies that there is also an optimal value of this parameter, and in the analysed case it is about 100 segments.

The effects of noise reduction can be also observed by analyzing the decay curves. They are obtained by the backward integration of the room IR. The upper limit of integration is set to be on the left edge of noise part as shown by the dashed line in Fig. 4(a). It is calculated as

$$t_{\text{int\_lim}} = T_{ss} \cdot \left[1 - B \cdot \left(\ln \frac{f_c}{f_1} \right) \Big/ \ln \frac{f_2}{f_1} \right] \qquad (2)$$

where B is the constant shifting the integration limit (here B=0.9 shifting slightly the integration limit towards the IR start), and f_c is the central frequency of the considered (e.g. third-octave) band. The decay curves obtained by integrating the IRs from Fig. 1(a) (with noise), 4(a) (the target curves), 4(b) and 4(e) (with reduced noise) are presented in Fig. 5.

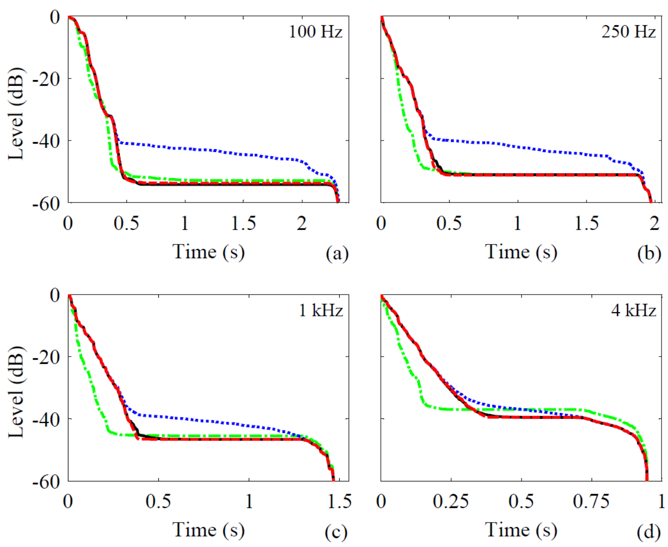

Fig. 5. Decay curves in the third octave bands obtained by the backward integration of the IRs from: (···) Fig. 1(a), (–) Fig. 2(a), (-·-) Fig. 4(b), (---) Fig. 4(e).

Due to the mentioned loss of the part of IR from Fig. 4(b), the decay curves for this IR are useless. However, the optimal application of the proposed noise reduction procedure illustrated in Fig. 4(e) leads to a significant increase in dynamic range, which in most curves at lower frequencies is even larger than 10 dB. These decay curves are almost identical to the target curves (obtained without noise in the response up to L). By increasing the frequency of the considered third-octave band, the reduction of noise effects becomes smaller (compare, e.g. Fig. 5(a) or (b) with 5(d)). So, the improvement in dynamic range at 4 kHz becomes of the order of several dB and further decreases at higher frequencies.

V. Conclusion

The proposed method for background noise effects reduction in the swept sine measurements of a room IR is rather efficient in the non-causal part or the IR where noise is significantly reduced. This can be of importance when the distortion products are analyzed. The proposed method also reduces noise in a part of the causal IR increasing the decay curve dynamic range. The increase is greater at lower frequencies and monotonically decreases towards higher frequencies. However, this is a desirable feature since the dynamic range is typically problematic at lower frequencies.

Acknowledgement

The presented results are obtained within the scope of the project no. 36026 financed by Ministry of Science and Technological Development of Republic of Serbia.

References

[1] G. Müller, M. Moser, *Handbook of Engineering Acoustics, Berlin*, Springer, 2013.

[2] S. Müller, “Measuring Transfer-Functions and Impulse Responses”, in *Part I: Acoustic Signals and Systems* edited by Finn Jacobsen in *Handbook of Signal Processing in Acoustics, Volume 1* edited by D. Havelock, S. Kuwano, and M. Vorländer, New York, Springer Science, 2008.

[3] D. G. Ćirić, M. Marković, M. Mijić, D. Šumarac-Pavlović, “On the Effects of Nonlinearities in Room Impulse Response Measurements with Exponential Sweeps”, Appl. Acoust., vol. 74, no. 3, pp. 375-382, 2013.

[4] S. V. Vaseghi, *Advanced Digital Signal Processing and Noise Reduction,* Chichester, England, John Willey & Sons Ltd, 2006.

[5] A. Farina, "Simultaneous Measurement of Impulse Response and Distortion with a Swept-Sine Technique", 108th Convention of the Audio Engineering Society, Abstract in J. Audio Eng. Soc., vol, 48, p. 350, 2000, Paris, France, 2000.

[6] M. R. Schroeder, “Integrated-Impulse Method for Measuring Sound Decay without Using Impulses”, J. Acoust. Soc. Am., vol. 66, no. 2, pp. 497-500, 1979.

[7] M. Karjalainen, P. Antsalo, A. Mäkivirta, T. Peltonen, V. Välimäki, “Estimation of Modal Decay Parameters from Noisy Response Measurements”, J. Audio Eng. Soc., vol. 50, no. 11, pp. 867-878, 2002.

[8] A. Farina, "Advancements in Impulse Response Measurements by Sine Sweeps", 122nd Convention of the Audio Engineering Society, Vienna, Austria, 2007.

[9] D. Ćirić, M. Milošević, “Transient Noise Influence in MLS Measurement of Room Impulse Response”, Acta Acust united Ac, vol. 91, no. 1, pp. 110-120, 2005.