Analysis of Background Noise Influence in Impulse Response Measurement by SineSweep Technique

Dejan Ćirić[1], Miloš Marković[2], Branko Stojić[3]

***Abstract* – Impulse response of a linear time invariant system represents one of its main characteristics. Unfortunately, there are some common problems in its measurement, especially in some cases, such as the measurement of a room impulse response in room acoustics. Independently of applied measurement technique, one of the most important problems is background noise.**

During the application of SineSweep technique for impulse response measurements, it is noted that the extracted impulse response contains "double horn" shape noise signal as a consequence of background noise. The influence of that noise is analyzed here by simulations and measurements. In addition, the analysis is extended to the cases where the system under test contains nonlinearity. Different impulse responses, that is, different systems are used as a test system including some filters and rooms. The results show that this specific shape of background noise in the extracted impulse response represents important negative characteristic that could affect further processing of the response. Besides, the shape of background noise in impulse response depends on present noise and the excitation signal parameters. Understanding of the background noise influence is very important for achieving high dynamic range representing an advantage of SineSweep technique.

***Keywords* – Background noise, Impulse response, SineSweep.**

I. Introduction

One of the most significant characteristics of a linear time invariant system is the transfer function and its equivalent in time domain – impulse response (IR). In room acoustics, impulse response of a room represents a fundamental characteristic for determining a number of room acoustic quantities [1]. Thus, measurements of room impulse responses require a high level of accuracy. Various methods and techniques have been used for this measurement [1-3]. Signals applied for excitation in the measurement process can be categorized in different ways. The most common broad-band signals are Maximum Length Sequence (MLS), which is pseudo-random white noise, and swept sine (SineSweep) – sine signal whose frequency varies with time.

During the measurement process, different room conditions can have influence on the measurement quality. Some of them can cause such negative effects so that obtained impulse response becomes useless [4]. One of the practical problems present in measurements is background noise (BN). In most cases, this noise is white Gaussian noise, non-correlated with the excitation signal. The main consequence of presence of background noise in an impulse response (IR background noise or IR BN) is decreasing of signal-to-noise ratio (SNR) or peak-to-noise ratio (PNR). Different measurement techniques are more or less immune to background noise. Some of them require a low level of noise for reliable results (the impulse excitation method). On the other hand, using MLS technique, high level of SNR can be obtained in real conditions because of its strong immunity to all kinds of noise (white, impulsive or others) [3]. The usage of SineSweep measurement technique allows the exclusion of all or most of the harmonic distortion products, leaving only background noise as a limitation for the achievable SNR.

The influence of background noise in measurements of room impulse response by SineSweep technique is analyzed here by computer simulations. The results are confirmed by measurements.

II. Background noise influence

Any measurement method using the excitation signal of equal length, spectral distribution and total energy will lead to exactly the same amount of noise rejection if the entire period of the unwindowed impulse response is considered. The difference between the various measurement techniques lies merely in the way that the noise is distributed over the period of the recovered impulse response [2].

MLS technique is able to randomize the phase spectrum of any component of the output signal which is not correlated with the MLS input sequence [5]. Any disturbing signal will be phase randomized, and this will lead to a uniform distribution of the background noise along the deconvolved impulse response, Fig. 1. Such a uniform distribution of IR background noise appears in most techniques for IR measurements. This noise limits impulse response decay to the point where the noise level is established. In this way, the dynamic range of impulse response is also limited.

III. SineSweep technique

Excitation signal in SineSweep technique is a sine signal with linearly (linear swept sine) or exponentially (logarithmic swept sine) varying frequency.

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

[2]Miloš Marković, Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: milos.markovic@elfak.rs

[3]Branko Stojić, Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: branko.stojic@elfak.rs

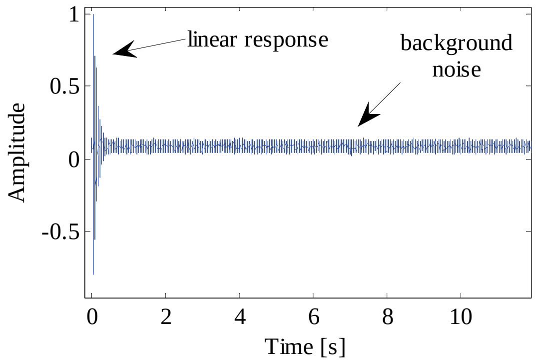

Fig.1. IR obtained by MLS technique

One of the main advantages of SineSweep technique is the possibility of obtaining a great dynamic range. The impulse response can be extracted either in time or in a frequency domain [6]. For linear deconvolution directly implemented in time domain, there is a need for proper inverse filter $f_{ss}(t)$ capable of transforming the excitation signal $x(t)$ into a delayed Dirac's delta function $\delta(t)$:

$$x(t) * f_{ss}(t) = \delta(t - t_d) \quad (1)$$

Then, the deconvolution of the system's impulse response $h(t)$ can be obtained simply convolving the measured output signal $y(t)$ with the inverse filter $f_{ss}(t)$:

$$h(t) = y(t) * f_{ss}(t) \quad (2)$$

The impulse response obtained in this way is twice as long as the excitation signal. Useful IR (linear response) starts at the moment delayed for the length of the excitation signal.

Another approach is to use a circular deconvolution in frequency domain. Impulse response can be obtained taking the IFFT of the transfer function:

$$h(t) = IFFT\left[\frac{FFT[y(t)]}{FFT[x(t)]}\right] \quad (3)$$

IV. Methods of Investigation

Background noise influence is analyzed through many simulations arranged in two groups. In the first one, Dirac's impulse is used as a pre-defined IR. This impulse is idealistic representation of impulse response. In the second group, instead of Dirac's impulse, simulated room IR is used. As an excitation signal, logarithmic swept sines of different durations are used. The duration of excitation signal is chosen to be equal to the duration of MLS signal for later comparison of SineSweep and MLS technique. Also, different background noises are generated. All of the BNs have Gaussian Probability Density Function (PDF), but their duration and level are different. All simulations follow the same method of investigation. Generated BN is added to the excitation sweep signal. That modified excitation signal is convolved with pre-defined impulse response. The result of this convolution is the output (response) signal with background noise. In the process of deconvolution, output signal is convolved with the inverse filter (generated on the base of excitation signal) yielding an impulse response with IR background noise present. This response is compared with starting (pre-defined) IR and the differences are observed. The influence of changing of BN parameters is considered, too.

In addition to the simulations, the background noise influence in SineSweep technique is analyzed in real conditions through the measurements of IR. Two types of measurements were performed: measurements of room IR carried out in one of the laboratories at the Faculty of Electronic Engineering in Niš and measurements of the band-pass filter IR.

V. Background Noise Influence in Simulations

A. Dirac's impulse as pre-defined IR

Dirac's impulse doesn't have all parts of real IR (e.g. room IR), but its shape is convenient for the analysis. If Dirac's impulse is used as a pre-defined impulse response, after adding background noise to the excitation signal, IR with background noise present is extracted only by the convolution of that signal plus noise (the modified excitation signal) with the inverse filter. For this group of simulations, the logarithmic sweep of duration equal to duration of MLS signal of order 16 is used as the excitation.

Without background noise, the extracted IR should be approximately equal to the starting Dirac's impulse delayed for the duration of the excitation signal. The results of analysis point out that when background noise is present a double horn shape signal (IR background noise) appears in the impulse response as a consequence of the background noise. The noise level in IR sets up gradually from the beginning of the response (region A), after reaching certain level, the noise level is increased but only slightly in relatively wide region (region B), and after reaching its maximum it is decreased also in relatively wide region (region C), Fig. 2.

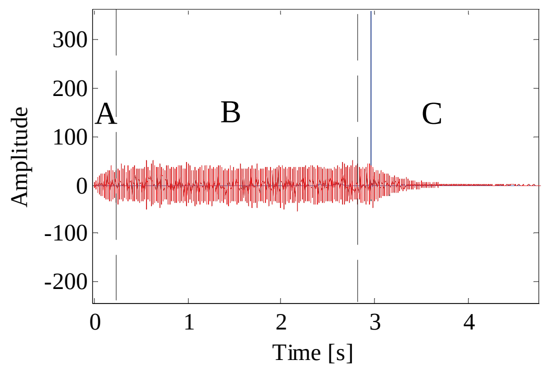

Fig.2. Three regions in double horn shape of IR background noise (red curve representing only the noise in IR without linear response) together with the linear response (blue curve representing zoomed linear IR)

The mentioned changing of the IR background noise level extends in both parts of the overall response, before and after the linear response. The limits of the noise regions (A, B and C) shown in Fig. 2 are only provisional, since it is difficult to make a clear distinction between the regions. These limits are also dependent on the length of the excitation sweep. Thus, the limit between the regions B and C (black dashed vertical line) could be in the first part of the response (before the linear impulse response) or it could be in the useful part of the linear impulse response.

The increase of the background noise amplitude (A_{BN}) leads to an increase of IR background noise amplitude (in the impulse response). The level of IR background noise (Mean Square Value (MSV) IR BN) is proportional to the level of background noise added to the excitation (MSV BN). Values of those levels for different background noise amplitudes (A_{BN}) are given in Table I. The ratio of MSV IR BN to the MSV BN is approximately $1.75 \cdot 10^3$ for all noise amplitudes.

TABLE I
LEVELS OF BACKGROUND NOISE

	A_{BN} [rel. units]				
	1	*2*	*4*	*8*	*16*
MSV BN10^3*	*5.46*	*21.7*	*87.1*	*348*	*1395*
MSV IR BN10^6*	*9.58*	*38*	*152*	*612*	*2450*

B. Room impulse response as pre-defined IR

Instead of Dirac's impulse response, this group of simulations uses room impulse response obtained by simulation algorithm [7]. This response is convolved with the excitation sweep yielding the output signal without background noise. IR without background noise is determined after the described deconvolution with the excitation (Eq. 2). This procedure is repeated when the background noise is added to the excitation sweep signal yielding as a result IR with background noise present. The logarithmic sweep signals of duration equal to durations of MLS signals of order 11 to 16 are used as the excitation.

The main characteristics of the IR background noise observed in the first group of simulations are present in this case, too. The IR background noise starts at the beginning of the IR, it is located in both parts of the overall response (before and after linear response) and the increase of noise level in the excitation leads to the increase of level of the IR background noise.

Impulse responses are then filtered in octave and one third octave bands, and IR background noise is analyzed. The background noise in the response is still non-stationary, but its shape is not completely the same as in broad band impulse response. Thus, at the beginning and at the end of the response there could be the region of the stationary background noise (region D). In the rest of the response, there is a region of more or less stationary background noise (region E), but of higher level than at the beginning and at the end of the response, Fig. 3. Between these two regions of two levels of IR background noise, the noise relatively suddenly increases and decreases its level (region F).

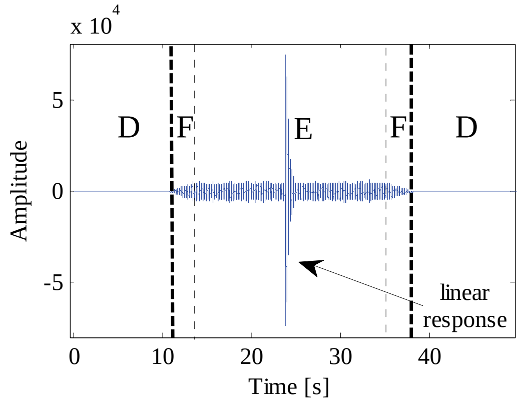

Fig.3. IR obtained by SineSweep technique and filtered in octave band at 800 Hz

Higher level region of IR background noise has approximately the same duration independently of the filter bandwidth (octave or one third octave). The length of this region depends only on the excitation signal duration. However, the filter central frequency, that is, the filter cut-off frequency determines the starting point of the higher level region: higher frequencies (wider filter pass-bands) move the starting point of higher level region towards the beginning of IR.

As a consequence of the regions with different noise levels, the noise level as well as PNR determination depends on the range in which these quantities are determined. Thus, one approach could be to determine the noise level in the range of higher noise level. Alternatively, the noise level could be determined in wider range, from the cross section of the linear response and noise to the end of the response. Of course, the noise level in the second case would be lower, that is, obtained PNR of IR would be higher.

The existence of non-stationary level of background noise implies also the problem of multi decay shape of the decay curve (integrated impulse decay). A typical example is given in Fig. 4, where the decay determined from broadband IR is presented together with the decay determined from filtered IR.

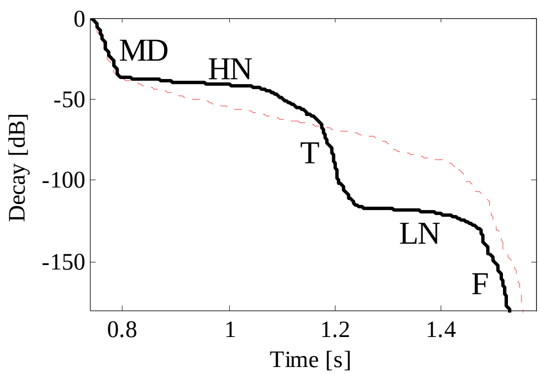

Fig.4. Decay curve obtained by backward integration of the broadband IR (thick black line) and IR filtered in octave band at 800 Hz (thin dashed red line)

Thus, instead of three parts, the decay curve consists of 5 parts. The first one is main decay (MD). The second part with smaller decay (HN) represents the region of higher noise level. The third part represents the first rapid fall of (T), and this is the region of transition between higher and lower noise level in the impulse response (the width of this region could be somewhat different in different impulse response, that is, in responses filtered in different octave or third octave bands). The fourth region represents the second region with smaller decay (LN), and this region corresponds to the last part of the response with lower background noise level, while the last part is the region of rapid fall of, because of finite upper limit of backward integration (F).

VI. BACKGROUND NOISE INFLUENCE IN MEASUREMENTS

A. Measurements of room IR

The influence of background noise in SineSweep technique is also analyzed in the measurements of room IR. Excitation sweep signals of durations equal to durations of MLS signals of order 15 to 19 are used. Extracted IRs confirm the expected results. The background noise in IR starts at the beginning of the IR, it is located in both parts of the overall response and the increase of noise level in the excitation leads to the increase of level of IR background noise. Besides, the shape of background noise in the filtered response is not completely the same as in broad band impulse response, as already noted in the results of simulations.

When the nonlinearity is present during the measurement of a room IR, the distortion products appear in addition to IR background noise, Fig. 5. Depending on the levels (amplitudes) of the products and noise, these products could be buried in the noise, that is, masked by IR background noise.

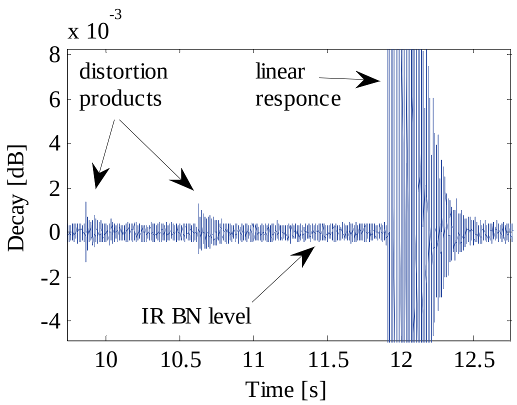

Fig.5. Measured IR: the distortion products are masked by background noise energy (zoomed IR)

B. IR measurements of pass-band filters

Measurements of IRs of two different filters, low- pass and high-pass filters are also performed.

Measured filters IRs indicate similar results as the simulations with filtered IR. Background noise in measured IRs is non-stationary, and it consists of two different levels, lower and higher. This could be explained by the fact that the IRs of these filters are not completely broad-band, but they contain only the part of the frequency range (the pass bands of the filters). Start moment of the higher level region is determined by the filter passband, that is, by its cut-off frequency.

VII. CONCLUSION

The presence of background noise in measurement of an IR by SineSweep technique results in IR background noise with double horn shape if the IR is broadband. This noise extends in both parts of the overall response (before and after the linear response). Level of the IR background noise is in proportion with level of noise present during the measurement. High level of background noise in IR decreases SNR and PNR of impulse response.

Filtering of broadband IR can change the IR background noise shape and its position in the response. The central frequency (cut-off frequency) of used passband filter (octave or third octave) determines the starting moment of higher level noise region. The existence of different levels of background noise in filtered IR implies the problem of multi decay shape of the decay curve. Thus, the decay curve obtained by backward integration of the filtered IR consists of five instead of three parts.

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REFERENCES

[1] L. Otshudi, J. P. Guilhot and J. L. Charles, “Overview of Techniques for Measuring Impulse Response in Room Acoustics”, *Proc. Institute of Acoustics*, **10**, pp. 407-414, 1988.

[2] S. Müller and P. Massarani, “Transfer-function Measurement with Sweeps”, *Journal of Audio Engineering Society*, **49**, pp. 443-471, 2001.

[3] G. B. Stan, J. J. Embrechts and D. Archambeau, “Comparison of Different Impulse Response Measurement Techniques”, *Journal of Audio Engineering Society*, **50**, pp. 249-262, 2002.

[4] D. Ćirić and M. Milošević, “Transient Noise Influence in MLS Measurements of Room Impulse Response”, *Acta Acustica un. With Acustica*, **91**, pp. 110-120, 2005.

[5] D.D. Rife and J. Vanderkooy, “Transfer-Function Measurement with Maximum-Length Sequences”, *J. Audio Eng. Soc.*, **37**, pp. 419-443, 1989.

[6] A. Farina, “Simultaneous measurement of impulse response and distortion with a swept-sine technique”, Pre-print of the *108th Convention Audio Engineering Society*, Paris, Abstract in *Journal of Audio Engineering Society*, **48**, pp. 350, 2000.

[7] A. Pantić, D. Ćirić, “Modeling of sound energy decay in room”, *Proceedings of LII Conference of ETRAN*, Palić, Serbia, 2008, paper AK2.5 (in Serbian).