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Impulse responses measured with MLS or Swept-Sine signals applied to architectural acoustics: an in-depth analysis of the two methods and some case studies of measurements inside theaters

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Abstract

The measurement of impulse responses inside of a room or a theatre is a critical task in architectural acoustics. The impulse responses are usually measured using either Exponential Sine Sweep (ESS) or Maximum Length Sequence (MLS) signals. The theory behind MLS generation and use is well developed and does not involve computational problems. When a non-linear system is measured, the distortion appears in the deconvolved impulse response as a series of peaks distributed over time, in deterministic positions. In case of presence of noise during the measurement, the phase of any spurious noise, even an impulsive one, is randomly distributed over the entire length of the recovered impulse response. The ESS signal shows some advantages over MLS, such as a better signal to noise ratio (SNR) and a robust non-linearity rejection. Typically, in the same conditions, the ESS has a dynamic range of about 15 dB higher than MLS. Nonetheless, the generation of an ESS signal and the subsequent analysis of impulse responses involve some problems whose solutions are not yet common practice and short impulsive noises can contaminate the sampled data, causing bad effects on the deconvolved impulse response, in form of a frequency decreasing sweep. For the above mentioned reasons ESS is generally more suitable than MLS for use in architectural acoustics, but in some cases the use of MLS signal is still to be preferred. Differences and advantages between impulse response measurements obtained by means of MLS or ESS, are analyzed and discussed in this paper and an in-depth analysis of both measurement methods is presented. Some case studies of impulse response measurements performed inside historical Italian opera houses using both MLS and ESS, in non-ideal conditions (for example in presence of spurious noise), are presented and examined, highlighting differences, advantages and pitfalls of both measurement methods.

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Keywords: MLS; ESS; Swept-sine; Architectural Acoustics; Impulse Response

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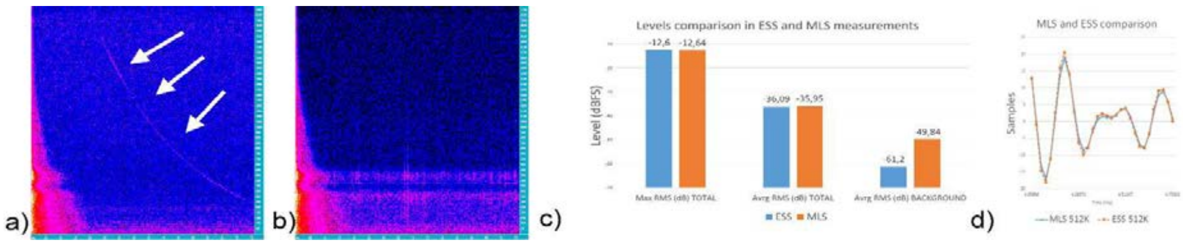

Fig. 1. (a) Spectrogram of ESS and (b) MLS measurements; (c) Peak and average levels of (a) and (b); (d) comparison (time data zoom)

1. Introduction

The use of a MLS (Maximum Length Sequence) signal for measuring impulse responses is well established [1], [2], [3]. The sine sweep signal is also widely used [4]. In particular, the ESS (Exponential Sine Sweep) signal has gained considerable interest since Farina introduced it in 2000 [5] and refined it in 2007 [6]. If compared to MLS , it reveals both advantages and drawbacks. The main advantage of the ESS method is the separation of the linear part of the measured impulse response of the system from most part of the harmonic distortion, even if recent studies have shown that some amount of odd orders distortion still remains, as Torras et al. [7] formally proved in 2011. The partial contamination of nonlinear distortion in the causal part of the impulse response had already been found in 2007 by Cirik in 2007 [8] and confirmed by other authors such as Kemp et al. in 2011 [9] and Dietrich et al. in 2013 [10] and Gusky et al. in 2014 [11]. The separation of the most part of distortion from the linear part allows having a much better signal to noise ratio (SNR) than with MLS, because the impulse response is free from the spurious peaks distributed on the time axis typically caused by distortion when using MLS. On the contrary, using ESS, the impulse response is recovered by means of an aperiodic linear convolution, avoiding the time-aliasing problem of MLS. Moreover, the use of an ESS measurement signal allows to describe easily the nonlinearities of the measured system by means of the Volterra model [12] and its simplified implementation (diagonal Volterra model). The crest factor of about 3 dB of the ESS can be exploited performing high power measurements in (steady) noisy conditions. Typically, in similar conditions the ESS has a dynamic range of about 15 dB higher than MLS.

2. Effect of impulsive background noise

Whereas stationary background noise can be somehow rejected and compensated in different ways for both MLS and ESS methods [11], impulsive noises can contaminate the data sampled using an ESS signal, causing spurious effects on the deconvolved impulse response in form of a frequency decreasing sweep [4], [6]. Figure 1 (a) shows an example of measurement taken using ESS inside a hall in presence of extraneous background activity causing impulsive noise (another example is shown in figure 4 (a)). Farina in [6] proposed a possible workaround for correcting a measurement corrupted by an impulsive noise, consisting in the rejection of the portion of the corrupted sampled ESS through a narrow-band filter, tuning the filter itself at the same frequency of the ESS at the very instant the disturbance occurs. However this procedure can be applied only if the sampled ESS is available and not when a measurement system gives in output directly the deconvolved impulse response. In addition, depending on the kind and duration of the disturbance, the manual correction of the ESS may not be possible.

Figure 1 (b) shows a MLS (single shot) measurement taken in same boundary conditions and at the same SPL as (a). The levels have been computed later (figure 1 (c)) from the impulse response data in dBFS scale (considering the maximum level measurable by the system equal to 0 dB). The maximum and average RMS levels on the two impulse responses are quite the same (the differences are around 0.1 dB), but, as expected, the background RMS level of the MLS measurement (computed from the part of the room response after the end of reverberation tail) is about 11.3 dB higher than the ESS measurement (even if also the ESS was corrupted by the impulsive noise). Besides the absolute levels, it is interesting to note the different distribution of the background noise over the frequency axis on the ESS and MLS measurements: in the ESS case (a) the background noise is equally distributed over the entire spectrum, while in the MLS case (b) the background noise has the same frequency fingerprint of the measured impulse response. The spurious peaks caused by distortion, typical of MLS method, are clearly visible in figure 1 (b).

3. Phase controlled ESS

Using MLS, the reconstruction by means of Fast Hadamard Transform of the measured impulse response provides ideal results; if the device under test has an unitary transfer function (performing a digital loopback measurement) the obtained impulse response is an ideal Dirac delta function, having therefore a perfectly flat frequency response. The generation and optimization of the ESS signal is trickier because the signal employed, unlike the MLS, does not cover the entire frequency analysis range (ideally infinite, but in case of measurement using a soundcard the whole range goes from DC to Nyquist frequency). For this reason, the “best” obtainable impulse response in this case is no longer an unitary pulse and some ringing around the main peak together with some ripple in the corresponding frequency response appear. The phase-controlled ESS signal employed in this work was proposed by Vetter and di Rosario [13], but actually the idea of a phase-controlled swept (also known as synchronized swept sine) has been introduced by Novak [12] in order to separate the several orders of harmonic distortion more clearly and to compute the Volterra kernels correctly. In this way, also the recovered linear impulse response will have the best possible “shape”. The ESS definition by Vetter and di Rosario, implemented here implicitly follows the Novak formulation, with some enhancements. The ESS signal is defined as:

$$x[n] = sin\left[\frac{\left(\frac{\pi}{2^P}\right)\cdot L}{ln\left(2^P\right)}\cdot e^{\frac{n}{N}\cdot ln\left(2^P\right)}\right] \tag{1}$$

$$\left(\frac{\pi}{2^P}\right)\cdot L = M\cdot\pi\cdot 2\cdot ln\left(2^P\right) \tag{2}$$

where n is the index of the generated sequence, P is an integer number of octaves, L the theoretical length of the ESS (floating point value), N the actual ESS length (equal to L rounded to integer) and M a positive non-zero integer. In this formulation, the signal contains exactly P octaves, the stop frequency of the sweep is always fixed at the Nyquist frequency and the start frequency is then π/2P radians. Once the number of octaves and the maximum length of the sweep are chosen, L, and then N, are computed from equation 2. A very small phase mismatch error remains because of the rounding of L. The time-reversed signal, used for the deconvolution, is then:

$$x^{-1}\left[n\right] = x\left[N-n\right]\cdot\left(2^{\frac{P}{N}}\right)^{-n}\cdot\left(\frac{P\cdot \ln(2)}{1-2^{-P}}\right) \tag{3}$$

It should be noted that the inverse signal computed using equation (3), required for the deconvolution of the impulse response, is generated starting from the test signal data, equation (1). Therefore, a weighting window applied to the test signal will be applied also to the inverse signal. Setting the higher frequency limit to the Nyquist frequency and spreading the ESS signal over an integer number of octaves, the distortion is separated and sorted as much as possible away from the causal part of the impulse response and the signal starts and stops with phase equal to zero, allowing better results. Some ringing and ripple still remain because the starting frequency of the ESS is not zero (the whole frequency range is not covered). A solution for obtaining a quite smooth spectrum, almost free from ripple, is the use of fade-in and fade-out windows on the generated signal. In order to find the optimal length and shape of these two fading windows, a compromise must be reached between two limit situations: i) a smoother frequency response and a worse impulse response, having higher ringing around the initial peak; ii) a frequency response having ripple at the extremes and a better impulse response, with less ringing around the initial peak. Depending on the intended use of the measured impulse response, case i), case ii) or a compromise between them could be more desirable.

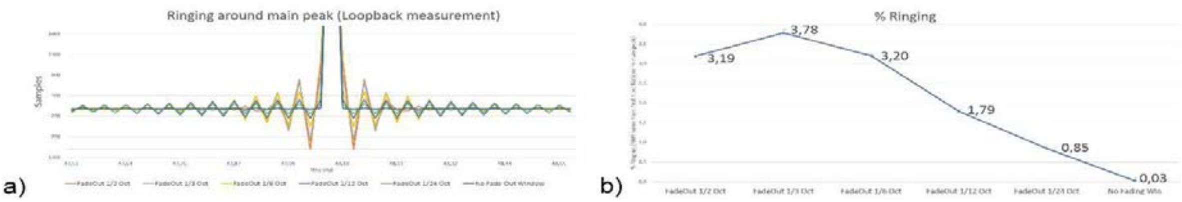

Fig. 2. (a) Ringing around the main peak for different Fade-out windows; (b) corresponding percentage ringing.

Figure 1 (d) shows some samples of a comparison between test measurements performed on a loudspeaker, in ideal conditions, using MLS or the ESS signal described above, zooming the amplitude of the plot: the matching is excellent. Figure 2 (a) shows the ringing in the time domain, around the peak, measured in a digital loopback configuration (unitary transfer function), using different fade-out window lengths. The ringing percentages shown in (b) have been evaluated as averages of the RMS values of the amplitude of the first 3 oscillations divided by the main peak amplitude. Without any fading window, the ringing percentage drops to the negligible value of 0.03% validating the described measurement procedure. Figures 3 show the effect of different lengths of the fade-in and fade-out windows, in order to minimize the ripple on the spectrum. These results have been obtained applying equations 1, 2 and 3 for the generation of the ESS and the impulse response computation. The ESS sequence was 512K samples long and the fade-in and fade-out windows were of the Hanning type (other types of weighting windows do give similar results). Measurements were performed using the same soundcard for playing and recording the ESS in real-time, avoiding clock mismatch problems. The behavior of the different fade-in windows lengths can be seen in detail in figure 3 (a); the amplitudes in dB of the first, higher, ripples are shown in Table 1. It can be observed that starting from a minimum length of 1 octave of the fade-in weighting window, the magnitude of the frequency response shows a quite smooth rounded shape in the initial part (the ripple disappears). Figure 3 (b) shows a comparison between the application of a 1/24 octave fade-out window and unweighted data; in Table 1 the ripple values are quantified. Any fade-out window length gives negligible ripple on the spectrum; without fade-out windowing a residual ripple of about 0.8 dB is found.

The specific application discussed in this work - room acoustics measurements - is not critical about the impulse response shape, it is thus preferable to priviledge the frequency response smoothness, applying a fade-in window of at least 1 octave (or longer) and a fade-out window of at least 1/24 octave.

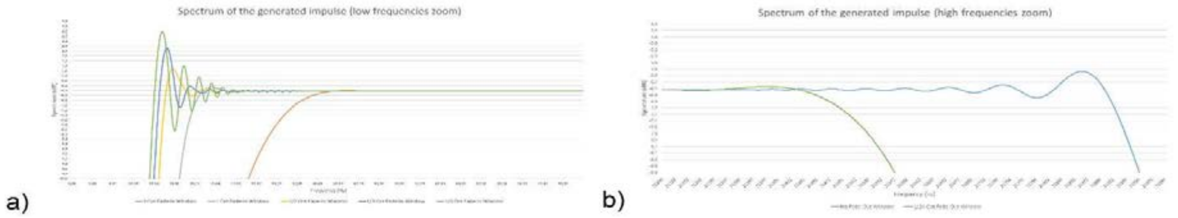

Fig. 3. (a) Zoom of the ripple at low spectrum end, different Fade-in; (b) zoom of the ripple at high spectrum end, differente Fade-out.

Table 1. Ripple for different fade-in and fade-out windows lengths.

Fade-In Window length	2 Oct	1 Oct	1/2 Oct	1/3 Oct	1/6 Oct
Max Ripple (dB)	<0.1	0.2	1.1	2.4	4.11
Fade- Out Window length	No Fading	1/24 Oct			
Max Ripple (dB)	0.8	<0.2			

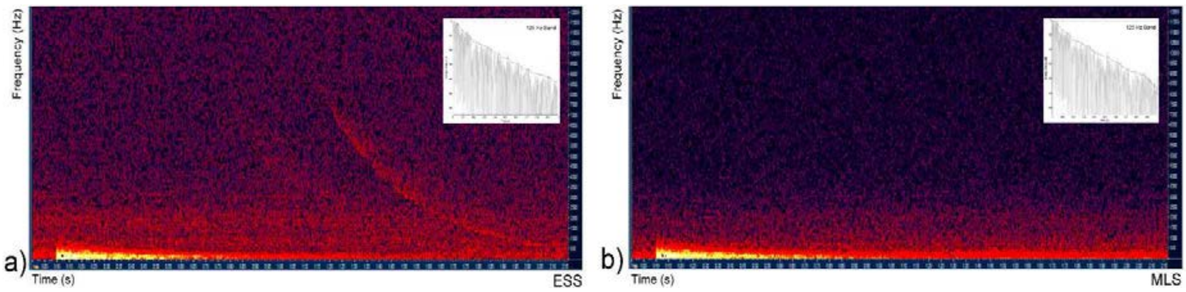

Fig. 4. Measurement in presence of impulsive noise with ESS (a) or MLS (b).

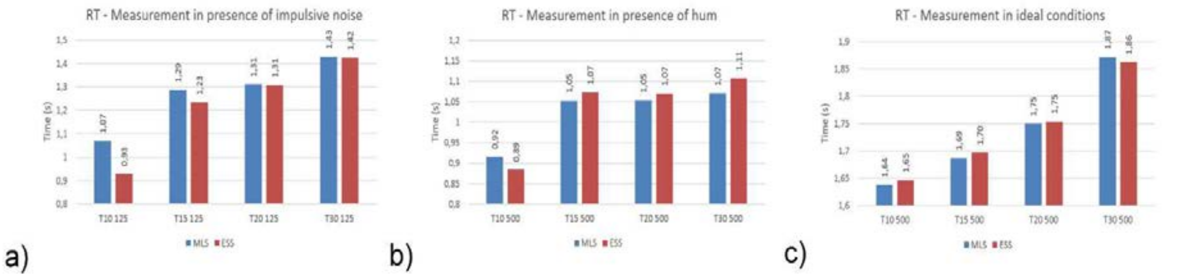

Fig. 5. Reverberation times (T10, T15, T20, T30) of example in figure 4 (a), figure 6 (b) and for a measurement in ideal conditions (c).

4. Case studies

Figure 4 (a) and (b) and figure 5 (a) describe a measurement performed inside a concert hall in presence of extraneous background activity causing impulsive noise. Four averages of MLS measurement and a single shot of ESS were taken. The sound source was a subwoofer, placed on the stage, therefore only the 63 Hz and 125 Hz octave bands were analyzed. All room acoustics parameters were computed using the ITA Toolbox package [14]. The effect of the impulsive noise in the ESS case can be seen in the spectrogram in figure 4 (a) as an inverse sweep; during the MLS measurement, the same impulsive noise was recorded, but the deconvolution of the MLS signal spread the disturbance over the entire time axis. Analysis of the background noise RMS level in both measurements shows that the (broadband) noise is about 10 dB lower in the ESS case. The impulsive noise is the cause of evident discrepancies in the computed reverberation time, especially T10 and T15 (figure 5 (a)). The energy / decay curves overlapped in figure 4 (a) and (b), for the 125 Hz octave band, reveal some (not evident) differences.

Figure 6 (a) and (b) and figure 5 (b) describe a measurement performed with ESS and MLS inside a concert hall with same configuration of previous case but the measurement was corrupted by a constant hum noise. The RMS background noise on both the measurements, in this case, is quite similar, with a difference of less than 0.5 dB (MLS has less noise), proving that the ESS method has a weak rejection also for steady tonal disturbances. Analyzing the 500 Hz octave band, the energy/decay plot of the ESS measurement, if compared to the MLS one, suggests a longer valid decay interval for the RT computation; the computed RT, represented in figure 5 (b), show some small differences.

Figure 5 (c) shows the RT computation of a measurement performed with ESS and MLS inside a concert hall in ideal conditions, without any disturbing noise. In this case the differences among the results are very small.

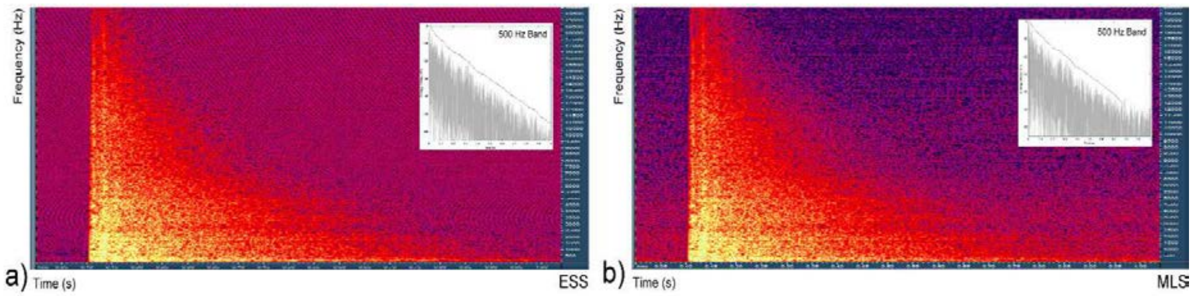

Fig. 6. Measurement in presence of low frequency hum with ESS (a) or MLS (b).

5. Conclusions

The ESS signal has some advantages over MLS, such as a better signal to noise ratio (SNR) and a robust non-linearity rejection, but some precautions should be taken in order to exploit its potential fully. Firstly, impulsive and steady tonal background noises should be avoided; in case of its occurrence, taking a new measurement is the best option. Not always the residual background noise gives reliable information about a corrupted measurement. Secondly, the generation of the ESS should be phase controlled and a data windowing targeted to the specific application of the measured impulse response should be applied, in order to optimize the results and avoid possible computation errors. The findings described in this work suggest that: i) the shape of the data window is not critical, provided it is smooth enough; ii) the fade-in window should be 1-octave wide, while the fade-out window should be 1/24 or 1/12-octave wide.

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