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Silence Sweep: a novel method for measuring electro-acoustical devices

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ABSTRACT

This paper presents a new method for measuring some properties of an electro-acoustical system, for example a loudspeaker or a complete sound system. Coupled with the already established method based on Exponential Sine Sweep, this new Silence Sweep method provides a quick and complete characterization of not linear distortions and noise of the device under test.

The method is based on the analysis of the distortion products, such as harmonic distortion products or intermodulation effects, occurring when the system is fed with a wide-band signal. Removing from the test signal a small portion of the whole spectrum, it becomes possible to collect and analyze the not-linear response and the noise of the system in that “suppressed” band. Changing continuously the suppressed band over time, we get the Silence Sweep test signal, which allows for quick measurement of noise and distortion over the whole spectrum.

The paper explains the method with a number of examples. The results obtained for some typical devices are presented, compared with those obtained with a standard, state-of-the-art measurement system.

1. INTRODUCTION

The author pioneered the usage of Exponential Sine Sweeps as test signal for the measurement of the transfer function and of the harmonic distortion of electro-acoustical systems [1].

It was later discovered that, from the results of a measurement performed with ESS, it is also possible to derive a subset of the Volterra Kernels (Diagonal Volterra Kernels), which allowed for the characterization and emulation (auralization) of devices having significant harmonic distortion [2,3,4].

However, this type of ESS measurements revealed also to cause some problems and artifacts; the solution of these problems and the removal of these artifacts was systematically addressed in [5].

What the ESS method does not measure, indeed, is the behavior of the system when excited with a more realistic test signal, containing many frequencies simultaneously, or a continuous wide band noise. In these cases, the system can often exhibit intermodulation distortion, or other not-linear effects, which are not properly evaluated employing the original ESS method.

Some authors attempted to overcome to this limitation employing multiple overlapped sine sweeps, as in [6].

Some ideas which inspired the born of the “Silence Sweep” method are found in a couple of divulgative articles written by Fabrizio de Leonardis on the Audio Review journal (in Italian), describing a method for measuring inharmonic distortion and noise, called Total Noise Distortion, which is based on a pair of test signals, containing a pink noise having one every two bands silenced (in a 1/3 octave band spectrum), so that the first signal only contains odd-order bands, and the second signal only contains even-order bands [7].

In this paper, a completely novel approach is employed: instead of leaving on or more silenced gaps in the spectrum, for collecting the distortion products, a wide-band continuous noise signal is “grooved”, creating a time-varying “suppressed band” in the spectrum.

Analyzing the response of the system inside the “suppressed band”, it is possible to quantify the spectrum of the distortion and of the noise, making it possible to assess its behavior under a more realistic signal.

2. BASICS OF THE METHOD

In this chapter the basic theory is explained, with an example referring to measurements performed with a “static” suppressed band. The reader is assumed to be confident with the usage of a standard waveform editor (Adobe Audition with Aurora plugins [8]).

The idea is to create a test signal which, at any instant, has a well-defined wide-band spectrum, for example white or pink. The spectrum will be continuous, with the exception of a small frequency range, where the signal is silenced (stop-band or suppressed-band).

For example, we can think here to use a white noise spectrum covering 10 octave bands (31.5 Hz to 16 kHz), in which we silence the signal inside just one octave band. The following picture shows an example of such “suppressed band” spectrum:

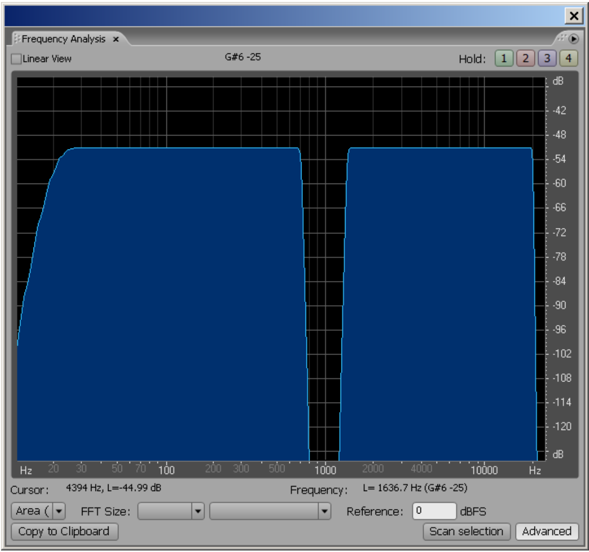

Figure 1 - 20Hz-20kHz White noise with the 1kHz octave band suppressed

We now assume to have an electro-acoustical system which is both affected by nonlinearities and by noise, as shown here:

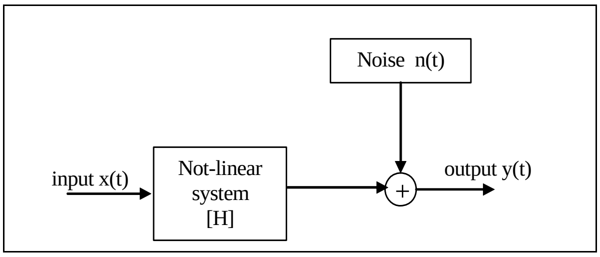

Figure 2 - Diagram of system's I/O

If we play the test signal (white noise with suppressed band) through the system, what we get as output is a quite different spectrum: outside the suppressed band the system has colored the spectrum of the test signal, which is not anymore flat. Inside the suppressed band, instead of zero energy, we have now some signal, representing both noise AND distortion products.

Figure 3 - Input spectrum (x) and output spectrum (y)

It can be observed that inside the suppressed band there is now a significant energy, and some evident peaks. This is the information collected with this type of "suppressed band" measurement.

For better understanding what of this signal is noise, and what is nonlinearity (distortion products), a traditional ESS measurement is performed as well, creating a 15s long exponential sine sweep, and playing it through the system under test.

After convolution with the inverse sweep, the system's linear impulse response is obtained, plus a number of harmonic-order responses.

Furthermore, a background noise measurement is performed.

The following figure 4 shows the spectra of the system's linear transfer function and of the background noise, with the same scale employed in fig. 3.

Comparing fig. 3 with fig. 4, it can be seen how the background noise was responsible of the measured system's response under 150 Hz, and how the peaks found inside the "suppressed band" are caused by the background noise, not by distortion.

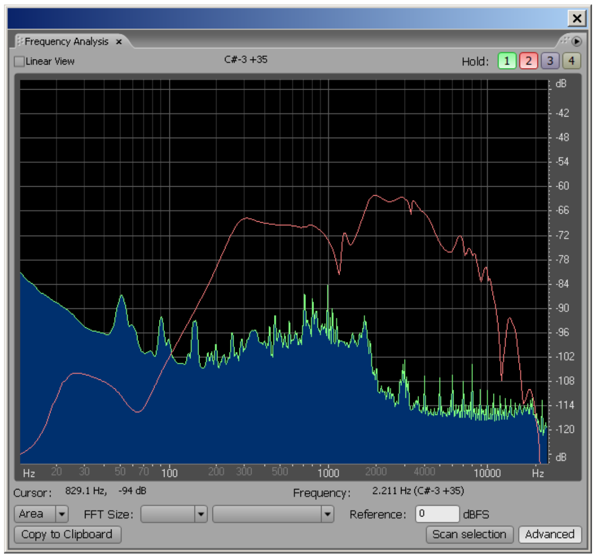

Figure 4 - Transfer Function and background noise

In the example shown here, distortion is very small. The following figure displays the spectra of the first 5 orders of harmonic distortion, measured with the ESS method:

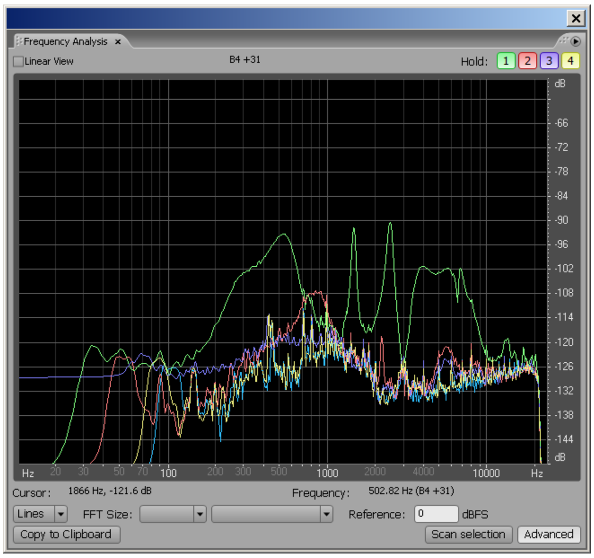

Figure 5 - Spectra of first 5 harmonic distortions

In fig. 5 it is quite evident that only 2nd-order harmonic distortion was significant for this device, but not in the 1 kHz octave band. Starting from 3rd-order distortion, the distortion products begin to be hidden below the background noise.

In other cases, however, the background noise becomes very small (for example, when electrical measurements are performed on a studio device, such as a compressor or another kind of effect). In these cases, the signal found in the suppressed band is dominated by distortion products.

The basic technique explained here can be employed for analyzing the whole spectrum, by repeating the measurement as many times as the bands to be analyzed.

However, as explained in the next chapter, it is possible to make just a single measurement, in which the suppressed band is swept over the frequency range during a reasonable time (for example, 15s). Some tricks are required, indeed, for efficiently creating the test signal and analyzing the response of the system inside the suppressed band.

3. THE SILENCE SWEEP TEST SIGNAL

"Grooving" a Silence Sweep in a continuous wide-band noise signal appears, at the beginning, a tricky task. One could employ a band-stop IIR filter, changing its parameters so that the stopped band sweeps progressively towards higher frequencies. This approach revealed to provide insufficient in-band attenuation, and to distort the phase around the corner frequencies of the stop-band filter.

Proper results were obtained employing a Sine Sweep as frequency-dependent time-delay filter.

We start generating the wide-band noise. For this, we employ the MLS signal generator:

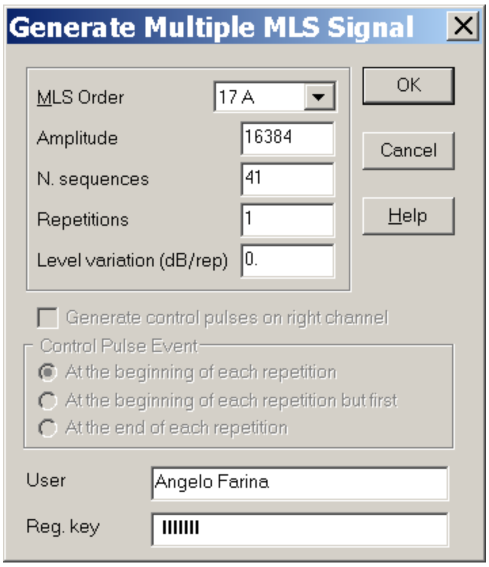

Figure 6 - Generation of MLS signal

The MLS signal obtained has a flat (white) spectrum, and this is substantially stationary over time.

We did create 41 repetitions of a signal which has a length of exactly 2^17 – 1 = 131071 samples, which corresponds to 2.73 s at 48 kHz.

We are now going to silence the central repetition of the MLS sequence, so that we will have 20 sequences, one silenced sequence, and other 20 sequences, as shown here:

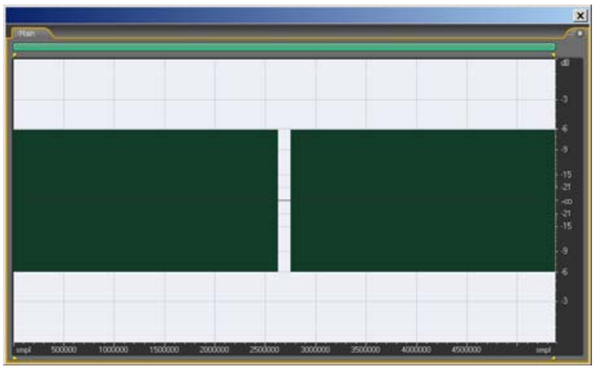

Figure 8 - MLS signal with silence gap

We are now going to create an Exponential Sine Sweep signal (which, indeed, will also be useful for performing the traditional ESS measurement of the device under test). This must be long exactly as 10 MLS sequences, so it will be 1310710 samples:

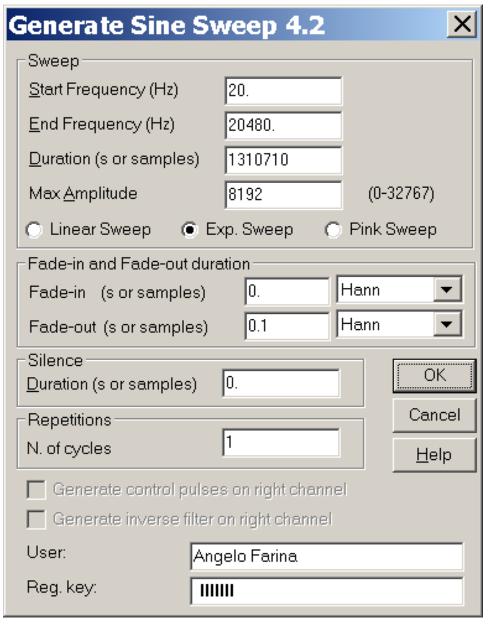

Figure 9 - Generation of a sine sweep

The Aurora plugin employed here also creates automatically the inverse sweep, which is saved for future use.

As our sine sweep signal was 1310710s long and spanning exactly 10 octaves (note that the upper frequency is exactly 1024 times the lower frequency of the sweep), we notice that the silence gap created in the MLS signal was 1/10 of the total length of the sweep, so that we will get a suppressed band exactly equal to 1/10 of the total frequency span, that is, exactly one octave.

We can now apply the sine sweep as a time-stretching filter to our MLS signal with muted central gap. For doing this, we load the sine sweep onto the Windows clipboard, and then we can convolve the MLS signal with the clipboard's content.

The following figure shows the sonogram of the band-suppressed MLS signal, before and after convolution with the sine sweep.

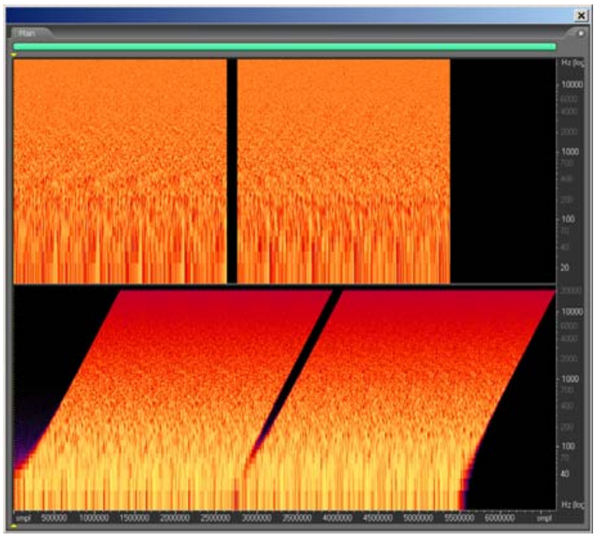

Figure 10 – MLS signal before and after convolution with the sine sweep

The convolution provided the effect wanted, that is, the silence gap is now swept over time. But it also provided another useful effect: the spectrum of the test signal is now band-limited pink, instead of band-unlimited white, as shown in the following picture:

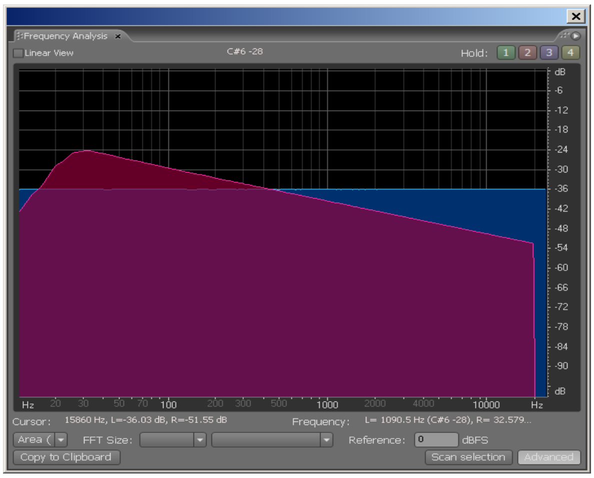

Figure 11 – Spectrum of the MLS signal before and after convolution with the sine sweep

The advantages of employing a band-limited pink noise as a test signal are well known for most devices.

Of course we now need to get rid of these "transient" parts at the beginning and at the end of the test signal. We can simply cut away the "tails" of it, for a length of exactly 1310710 samples. At the end, we obtain the following final test signal:

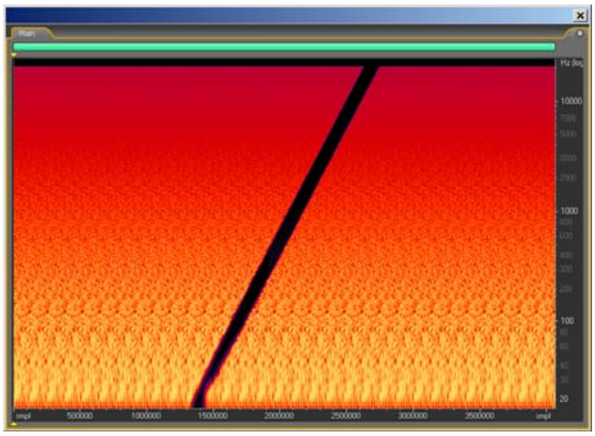

Figure 12 – Sonogram of the "Silence Sweep" test signal

We can now use our test signal, playing it through the device under test, and recording the system's response.

In the following picture, an example of such a measurement is shown:

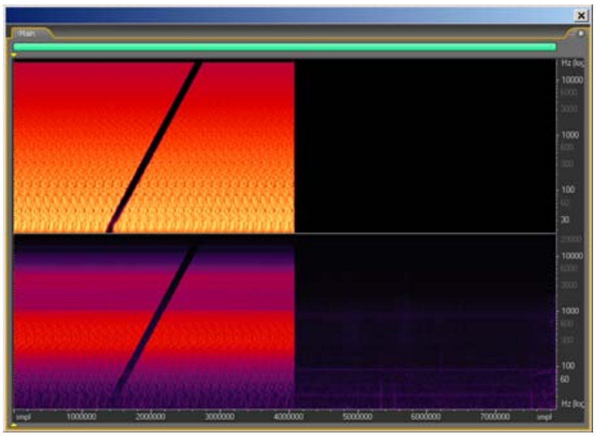

Figure 13 – Example of "Silence Sweep" measurement

In fig. 13 it can be seen how inside the "silence groove" we have recorded some signal, caused by background noise and nonlinear distortion products. Please notice also how the recording was continued after the end of the test signal, so that the background noise is recorded.

For retrieving the information captured inside the "groove", we need to de-stretch it over time. This is performed by convolving the measured signal with the "Inverse Sweep" signal already obtained when the sine sweep was generated.

After convolving with the inverse sweep both the test signal and the system response, we get this picture:

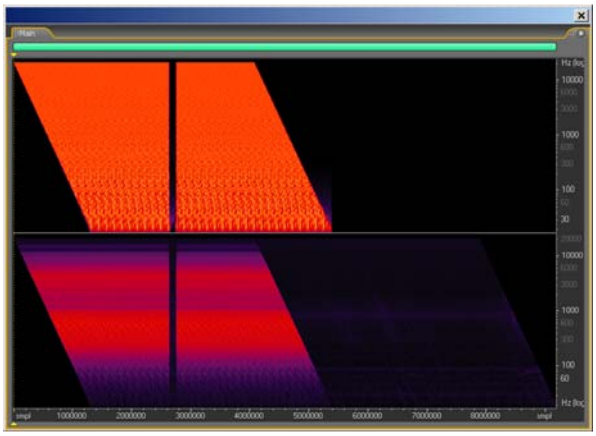

Figure 14 – Test signal and measured system's response after convolution with the inverse sweep

We better throw away, again, the beginning and final tails (1310710 samples long, as usual):

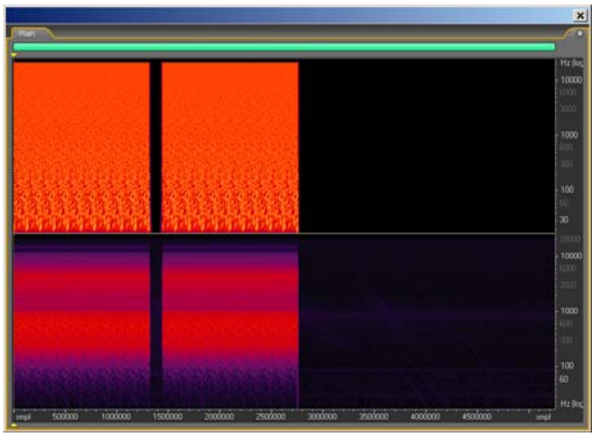

Figure 15 – test signal and measured system's response after convolution with the inverse sweep

We can now analyze separately the time segments when the signal was active (the first 1310710 samples) and the following 131071 samples, during which there was no signal, and the system's response is only due to background noise and distortion. Also the segment at the end, where the background noise was captured, can be analyzed, providing info on the background noise only.

The following figure shows the spectra obtained when performing this comparison:

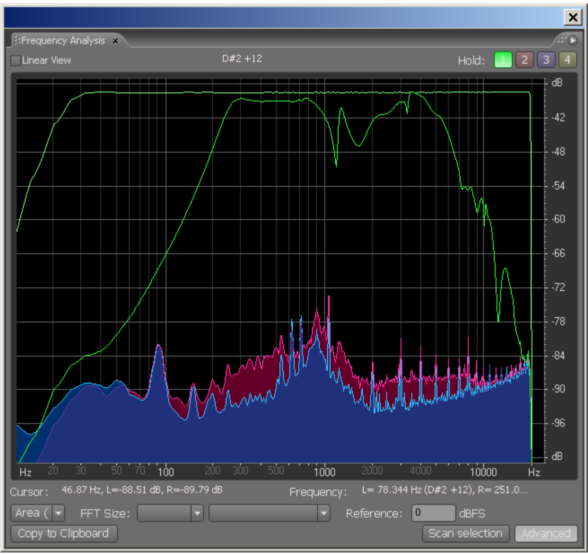

Figure 16 – spectra of test signal, system's linear response, THD+Noise and Noise

The signal measured inside the "silence groove" is the loudest spectrum shown with solid area. The other "solid" spectrum is the background noise. The two spectra shown with thin lines are the test signal (perfectly flat, as the convolution with the inverse sweep restored the "white" spectrum of the MLS signal), and the system's linear frequency response.

It can be seen how the spectrum obtained analyzing the signal captured inside the "groove" is mostly dominated by distortion products: only at a few frequencies the effect of the background noise dominates, where some peaks emerge from the random noise floor, caused probably by fans or other rotating equipment.

4. ADVANCED ANALYSIS

It is possible to perform a more advanced analysis, employing the properties of the MLS signal employed as wide-band noise carrier.

After the recorded signal has been de-stretched (by convolution with the inverse sweep), it is possible to perform standard MLS deconvolution.

Efficient MLS deconvolution is possible employing the Fast Hadamard Transform (and an Aurora plugin is available for this). However, in this case we prefer to employ the good, old trick of computing the correlation of the recorded signal with the original MLS sequence, which makes it possible to get an independent impulse response for each of the 10 sequences preceding and following the "suppressed band" sequence.

In practice, the correlation is obtained convolving the measured signal with the time-reversal of a single MLS sequence. After the convolution, we get this:

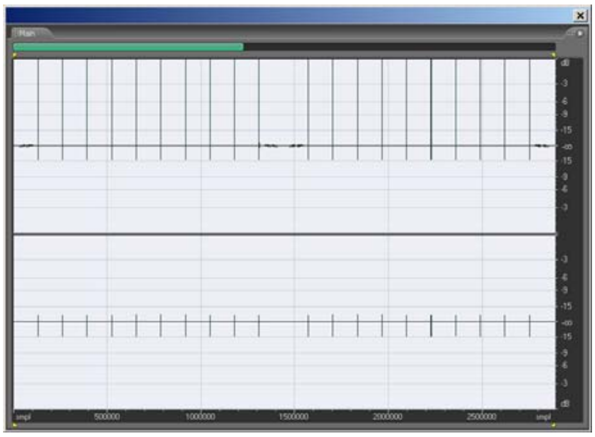

Figure 17 – Impulse responses obtained after MLS deconvolution

We can now simply select one of the intermediate IRs (not the first or the last of each group, as these are affected by some "border irregularities"), and perform an FFT analysis, which provides the following result:

Figure 18 – spectra of test signal and system's linear response from MLS deconvolution

These spectra are very similar to those obtained by analyzing the signals before MLS deconvolution, but smoother and cleaner, due to the improved S/N ratio.

However, the MLS analysis is known to have troubles when dealing with strongly nonlinear devices. So it is better to re-measure the linear impulse response of our device employing the Exponential Sine Sweep method.

We have already generated a suitable ESS signal, which was employed as a time-stretching filter during the creation of the "Silence Sweep":

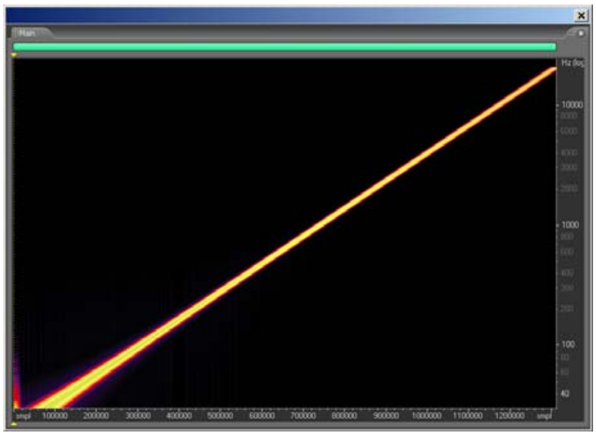

Figure 19 – Exponential Sine Sweep signal

We now perform another measurement of the electro-acoustical system under test, playing the ESS signal (at the sample RMS amplitude as before), and recording the system's response. Here is what we get:

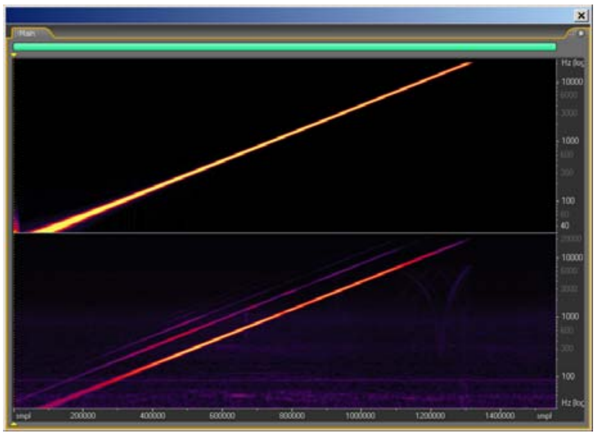

Figure 20 – Exponential Sine Sweep signal and system's output signal

In the above figure it is quite evident that the system is creating significant harmonic distortion, represented by the lines running above, and parallel to, the main sweep.

After convolving with the inverse sweep, we get the following impulse responses:

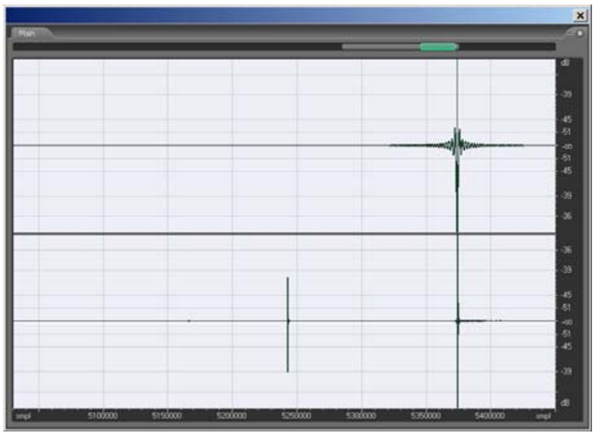

Figure 21 – Exponential Sine Sweep signal and system's output signal

In practice, only the 2nd-order distortion peak is visible in the above picture, due to the linear vertical scale. When the spectra of the harmonic orders are computed, the following figure is obtained.

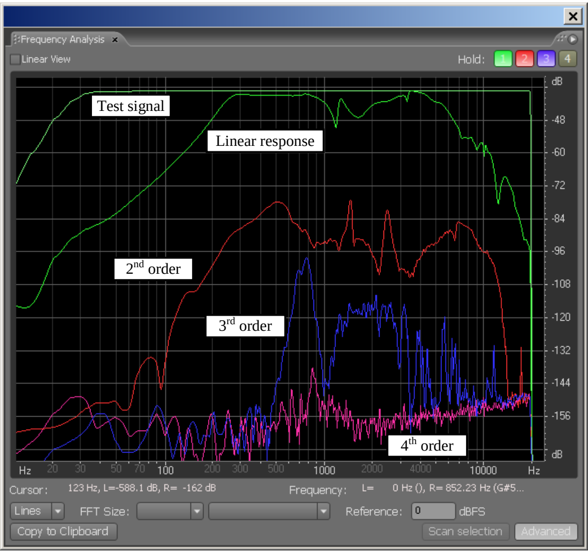

Figure 22 – Spectra of test signal, linear system's response and of harmonic distortions of order 2, 3, 4.

It can be seen that the 2nd-order distortion is significant, whilst 4th order and above substantially disappear in the noise floor of the measurement system.

It can be interesting to compare the spectrum of 2nd order distortion with that of the total distortion plus noise obtained with the "silence sweep" test signal. The following picture shows this comparison.

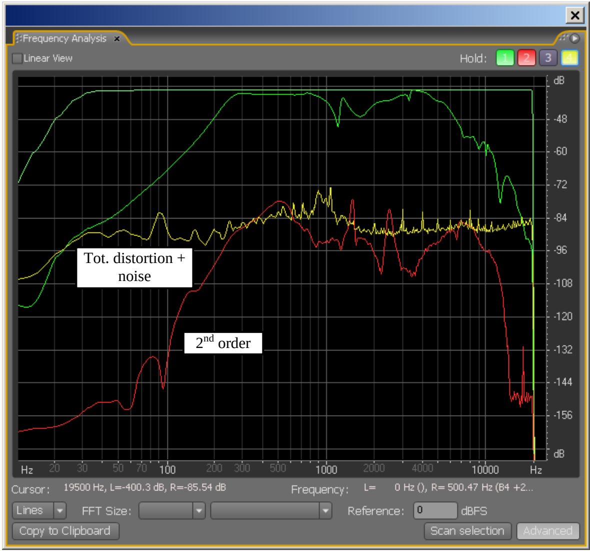

Figure 23 – Comparison of harmonic distortions of order 2 and total distortion + noise.

It can be seen that, at some frequencies, the spectrum of the 2nd-order distortion exceeds the spectrum of the total distortion plus noise. This looks suspicious, probably when the system is fed with a pure tone, it tends to exhibit significantly more harmonic distortion than when fed with a pink-noise signal having the same RMS value.

5. DISCUSSION

The new measurement method provides a "quick and dirty" estimate of the nonlinear behavior of an electro-acoustical system, including noise, harmonic distortion, intermodulation distortion and inharmonic effects (such as "rub and buzz", rattling, etc.).

However, once the total result is obtained, it is not easy to separate the various contributions. So it is recommended to employ the new "Silence Sweep" method in conjunction with already established methods, in particular with ESS. Also recording a sample of background noise is useful.

In practice, it is advantageous to create a standard all-inclusive test signal, made of the sequence of the Silence Sweep signal, a piece of silence, and an Exponential Sine Sweep, as shown in the following figure:

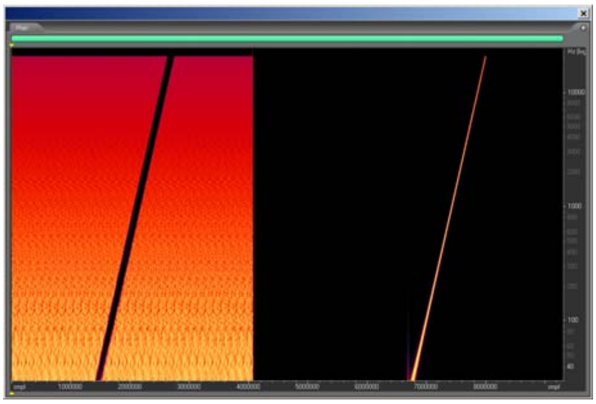

Figure 24 – All-inclusive Silence Sweep, Silence and ESS test signal.

Please notice that the sweep employed for generating the Silence Sweep is exactly the same subsequently employed for the traditional ESS measurement.

This makes it possible, after the measurement is done, to convolve everything with the same Inverse Sweep: this will restore both the unstretched silence gap in the first part of the measured signal, and the series of impulse responses in the second part.

The following figures show the result of a measurement performed employing the "all inclusive" test signal, and the same after convolution with the inverse sweep, and after rescaling to full range the first part (as the signal was rescaled to full range with reference to the maximum amplitude of the linear response, which is much louder than everything else).

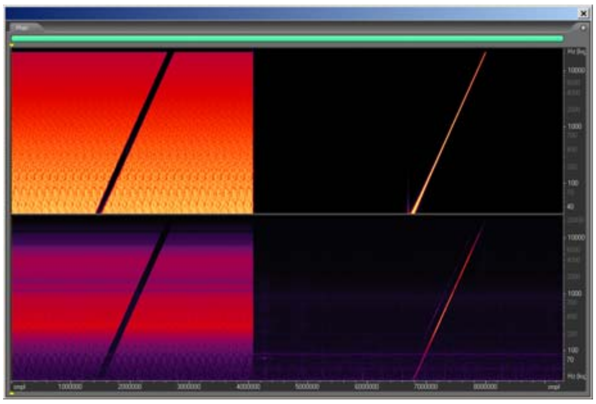

Figure 25 – Measurement employing the all-inclusive Silence Sweep, Silence and ESS test signal.

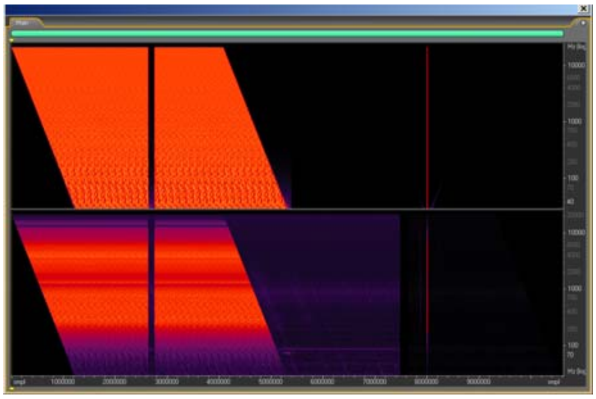

Figure 26 – The same, after convolution with the inverse sweep and gain normalization.

By properly analyzing all the portions of the results (silence gap, background noise, linear IR, 2nd order IR, etc.), the following "all inclusive" chart can be obtained:

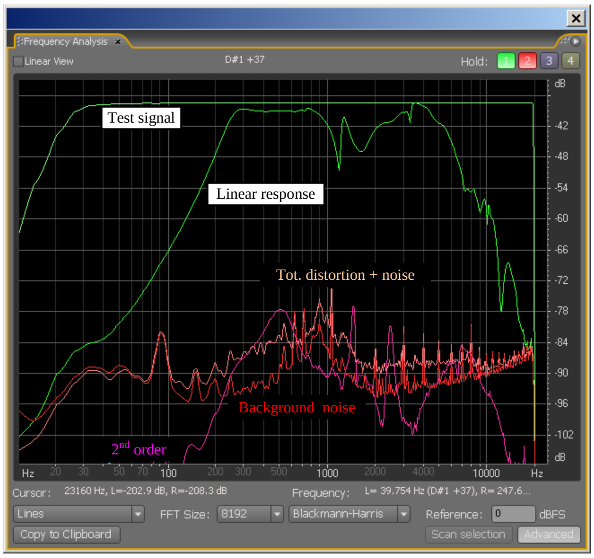

Figure 27 – Simultaneous determination of the spectra of the test signal, linear system response, 2nd-order harmonic distortion, total distortion+noise, and background noise

It is still objectionable the fact that the measurement with the "silence sweep" method is performed with the same RMS amplitude as the Exponential Sine Sweep.

This choice causes the fact that the harmonic distortion measured by ESS is significantly stronger than the total distortion measured by the Silence Sweep, as the first concentrates all the energy at a single frequency, whilst the second spreads it out over a spectrum which is 10 octave bands wide (albeit one octave band is being silenced).

6. COMPARSION WITH A STATE OF THE ART MEASUREMENT SYSTEM

At the time of writing this preprint, the results of a systematic comparison between the new measurement technique and a state of the art laboratory system were not yet available.

However, these results will be included in the oral presentation, and they will be made available on the web site of the author, in the same area where the signals employed for the examples presented here are posted [9].

A brief description of the experiment actually undergoing is provided here.

The Silence Sweep method was implemented on a Windows PC, running Adobe Audition 3.0 and the suite of Aurora plugins version 4.2. The PC is equipped with an external semi-professional sound card (Motu Traveler Mark 3), which allows for the usage of ICP-powered measurement-grade class-I microphones (Bruel & Kjaer type 4189, with preamplifier type 2731).

The reference system was a laboratory-grade multichannel analyzer (Audio Precision APx 585, kindly donated by Audio Precision Inc.).

The systems under test are two: a good quality pair of loudspeakers employed in a small monitoring room (Quested F11P, powered by a QSC PLX 1200 power amplifier), and a set of headphones (Sennheiser HD580).

The measurements were performed at various voltages, and it was analyzed how the total distortion increases with the driving voltage.

Albeit the measurement with the Silence Sweep resulted to be much slower than the fast ESS employed in the APx 585 analyzer, it revealed capable of detecting some "subtle" inharmonic problems affecting one of the two loudspeakers in the pair, caused by some loose particles inside the box.

7. CONCLUSIONS

The new "Silence Sweep" method revealed to be capable of assessing some peculiar nonlinear effects occurring in electro-acoustical systems, making it possible to spot out manufacturing problems and other acoustical and structural effects.

The most obvious field of application will be the quality control of loudspeakers and sound systems. However, some other possible fields of application include:

- Detection of structural problems in buildings and enclosures (rattling, loose parts, etc.)
- Not-destructive analysis of paintings and walls
- Analysis of structural damage and proper restoration in musical instruments

8. ACKNOWLEDGEMENTS

The Audio Precision analyzer employed as a reference test system was kindly donated to the University of Parma by Audio Precision Inc, USA.

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