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BUILDING AND ROOM ACOUSTICS MEASUREMENTS WITH SINE-SWEEP TECHNIQUE

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1. ABSTRACT

New measurement methods based on digital signal processing bring a number of advantages compared to well-established classical methods for the measurements in building and room acoustics, such as extended signal-to-noise ratio (SNR) and high distortion immunity. Importance of these techniques is confirmed by the fact that the International Organization for Standardization (ISO) is working on a standard for applications in building acoustics. The paper presents a real-time implementation of this measurement method, based on excitation with an exponential sinusoidal sweep and focuses on its practical use and benefits. Comparisons with methods based on maximum-length sequence techniques are also given.

2. INTRODUCTION

Most of the measurements in building and room acoustic are based on postprocessing of the impulse response i.e. extracting the data from it. Frequency dependent reverberation time and noise insulation i.e. level difference between source and receiving room are just some of acoustical parameters obtained from the impulse responses.

M. Schroeder showed that backward integration of the impulse response h(t) results in Energy Decay Curve (EDC), which corresponds to the remaining energy in the impulse response after time t:

$$E\{r^2(t)\} = N_0 \int_t^\infty h^2(t)\,dt$$

where $r(t)$ is the measured response and N_0 is a constant specifying the spectral density of the noise. Reverberation time is measured by estimating the slope of this curve as described in ISO3382. The EDC can be used to measure the level versus time:

$$L(t) = 10\log\left\{N_0 \int_t^\infty h^2(t)\,dt\right\}$$

or for determining the noise level in the room during excitation:

$$L_0 = L(0) = 10\log\left\{N_0 \int_0^\infty h^2(t)\,dt\right\}$$

Those are just some of numerous ways in which an impulse response can be processed, but the number of ways in which it can be obtained is significantly smaller. Traditionally, pulse excitation or interrupted noise has been used as excitation in such measurements. The impulse response (IR) or decay curve is obtained directly as response to such excitation, i.e. without any special signal processing involved. Correlation based techniques with maximum length sequence (MLS) or swept sine as excitation signal brought further improvements in obtaining IR. In the 1980s, the popularity of MLS based techniques has grown due to the ability to use computer features available at that time. Nice features, such as extended SNR, could then be provided. The signal processing behind an MLS measurement is usually based on the Fast Hadamard Transform. An MLS-signal can be generated by using only shift registers and XOR gates. Both of those features were important in the 1980s, but have vanished with the appearance of today's processors. MLS based techniques have some undesirable properties such as vulnerability to distortion and time variance. Those undesired properties motivated the research of new measurement methods. The results of that research, presented in [1, 2] represent the foundation for sine-sweep technique, which cures the weaknesses of MLS and further brings numerous other advantages.

All those facts as well as the efforts of International Organization for Standardization (ISO) to standardize the method for applications in building acoustics [3], motivated the implementation of sine sweep based measurement as a feature of a sound analyser.

3. SINE-SWEEP TECHNIQUE

The response of linear-time-invariant (LTI) system to excitation *x(t)* can be obtained as convolution of its impulse response *h(t)* and excitation signal:

$$y(t) = \int_{-\infty}^{\infty} x(t)h(t-t)dt$$

The Fourier transform of this equation shows that the spectrum of the response signal is equal to the product of the spectrum of the input signal and the frequency response function of the system:

$$Y(w) = H(w)X(w)$$

Therefore, the frequency response function can be obtained by dividing the spectra of response and excitation:

$$H(w) = \frac{Y(w)}{X(w)} = \frac{F\{y(t)\}}{F\{x(t)\}}$$

The impulse response of the system is obtained by means of inverse Fourier transform of such a quotient:

$$h(t) = F^{-1}\{H(w)\}$$

This mathematical convenience is used to design the system for measurement of IR with sine sweep technique as presented in figure 1. Deconvolution of the received signal with excitation signal is performed by division in the frequency domain. In the system presented, this is performed by calculating the FFTs of these two signals and dividing them. IFFT of the quotient corresponds to the measured IR. An alternative to this is filtering with a filter whose frequency response function corresponds to the inverse of the excitation

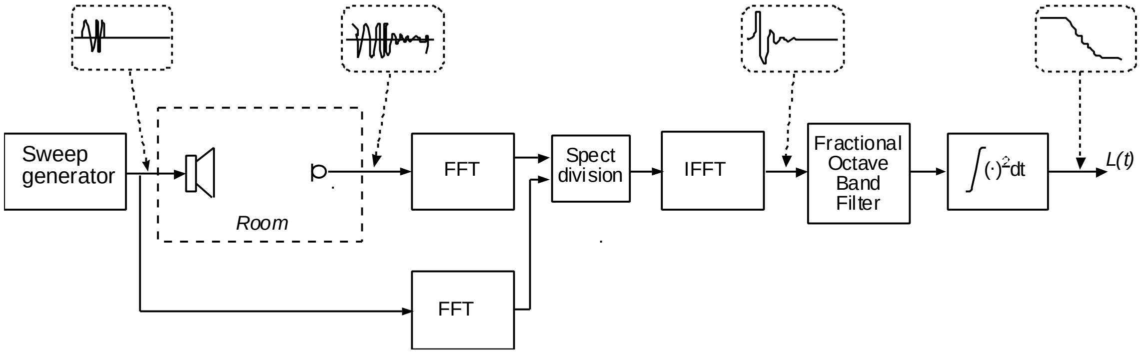

Fig. 1 S*ystem for obtaining the decay curve by means of sine sweep*

signal spectrum, as described in [2].

Any kind of excitation signal, which contains sufficient energy at every frequency of interest, can be used to determine the impulse response or the frequency response function of any linear and time-invariant system. Sine sweeps are relatively easy to generate and reproduce. Additional convenience is that the sinusoidal excitation signal can be fed with substantially more power than an MLS-signal. The sweep also makes it possible to control the shape of the spectrum by modifying the sweep-speed. The exponentially swept sine is suitable for measurements in building and room acoustics as it provides the same energy in each fractional-octave band. The spectral response will then have a decay of 3 dB/octave just as pink noise, which in classical methods is used for excitation.

Increasing the sweep duration feeds more acoustic energy into the room to be measured, and thus increases the effective signal-to-noise ratio. In room and building acoustics, the reverberation time is normally longest for the lower frequencies. When very long sweeps (many seconds) are being used, the final gap only has to accommodate the reverberation at the highest frequencies, which generally is short. This holds because all the lower frequency components arrive while the excitation signal is still sweeping upwards, as depicted in figure 2. Therefore, an exponential upward sweep provides a shorter gap i.e. shorter overall measurement time than sweeping in the other direction. But even more

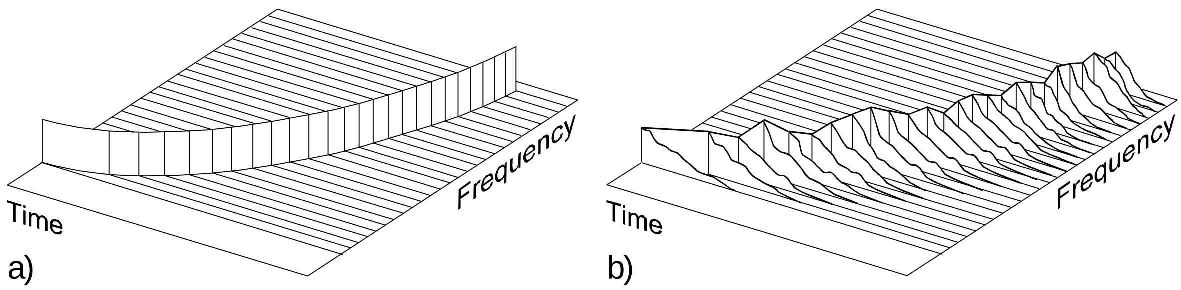

***Fig. 2** Time frequency diagram for an exponential sweep. Part a) shows the excitation and b) the response.*

important feature of upward sweeps is that they give the ability to separate harmonic distortion components from the measured IR, by means of zero padding prior to the FFT [1, 3].

4. COMPARISON OF MLS AND SINE SWEEP PERFORMANCE

The MLS technique has been widely used in acoustical measurements due to its positive features compared to classical methods, such as reduced statistical spread of results, enhanced SNR and an reduced lower limit for the measured reverberation time. However, MLS inherently contains some disadvantages. The huge potential of sine sweep technique lies in the fact that they do not suffer from these disadvantages. Periodic deterministic noise sequences (such as MLS) are extremely vulnerable to even a slight time variance. Increased measurement length is often used in order to further increase SNR of an MLS measurement. Unfortunately this also increases vulnerability to time variance. Sweep and impulse measurements do not display this unfavorable behavior [1].

With sweep techniques higher loudspeaker output levels can be used. This will result in higher level of excitation signal (highly desirable feature as it increases SNR) but may also cause harmonic distortion due to the nonlinearity of the loudspeaker. This distortion will appear in impulse responses obtained by MLS and sine sweep in two different ways. In an MLS measured response, the distortion will appear as spurious peaks. This reduces the SNR and may deteriorate the measured IR in such an extent that it limits the applications. On the other hand, the effects of harmonic distortion can be removed when the impulse response is measured with the sweep technique. Double size of FFT and zero-padding makes distortion components appearing at negative times and these components can be removed by windowing. This useful feature also makes it possible to reduce the size and weight of the loudspeaker for excitation.

Another advantage is that sweep technique have less requirements for clock synchronization between the excitation and the measured response compared to an MLS based system. Furthermore, the Nor121 based implementation contains automatic detection of start of the sweep. This allows the use of a pre-recorded excitation signal or a signal generated by another instrument.

5. IMPELENTATION IN SOUND LEVEL METER NOR121

With all the mentioned theory behind it and beneficial features it provides, a modern technique such as sine sweep has been recognised as a unique implementational challenge by us at Norsonic. The full advantages of sine sweep based measurements, which can provide SNR in excess of 100 dB, cannot be exploited in cases where the input dynamic of the instrument is limiting the SNR of the result. Therefore, the Norsonic Nor121 sound analyser with its 120 dB dynamic range and widely used building acoustics measurement mode was a logical choice as a platform for the implementation. The existing user interface in the building acoustic mode has been kept with small extensions. The sine sweep generator and the whole measurement algorithm are installed in the instrument as a software option.

Normally, in building and room acoustic measurements, the aim is to obtain results in octave- or third-octave bands. This can be achieved in two ways. One of them is used with MLS (as in real time analyser Norsonic Nor840) and contains three steps: measurement of

broadband impulse response, it's filtering into desired subbands and measurement of acoustical parameters from those post-processed IRs.
An alternative is to perform separate measurement of impulse response for each subband and measure acoustical parameters directly. Example of this method is filtered pink noise excitation and serial analyses.

Measurement of separate IR for each subband has been chosen in our implementation of the sine sweep method. The acquisition time for recording the sweep response has to be longer than the sweep itself (to collect the reverberated sound). Literal application of this technique would mean that a separate sweep with a period of silence would be necessary for each subband. This would increase the overall measurement time.

A solution based on one continuous sweep through all of the subbands has been developed. The energy in the subband of interest has to be separated from the energy in other subbands. This is done by time and frequency domain windowing. For this purpose hybrid windows have been developed. Those windows had to satisfy a number of constraints. Most important, they have to satisfy the frequency response requirements for a class 1 fractional-octave filter as specified in IEC 61260 and to have a short virtual reverberation time.

With present implementation, it is possible to measure in octave or third-octave bands within the frequency range 50 Hz to 20 kHz i.e. 9 octaves or 27 third-octave bands. Sweep durations of 19.2 s for octave and 38.4 s for third-octave bands have been chosen. The measured SNR may exceed 100 dB. The length of the measured IRs is more than 10 s at 50 Hz to more than 2 s at 20 kHz.

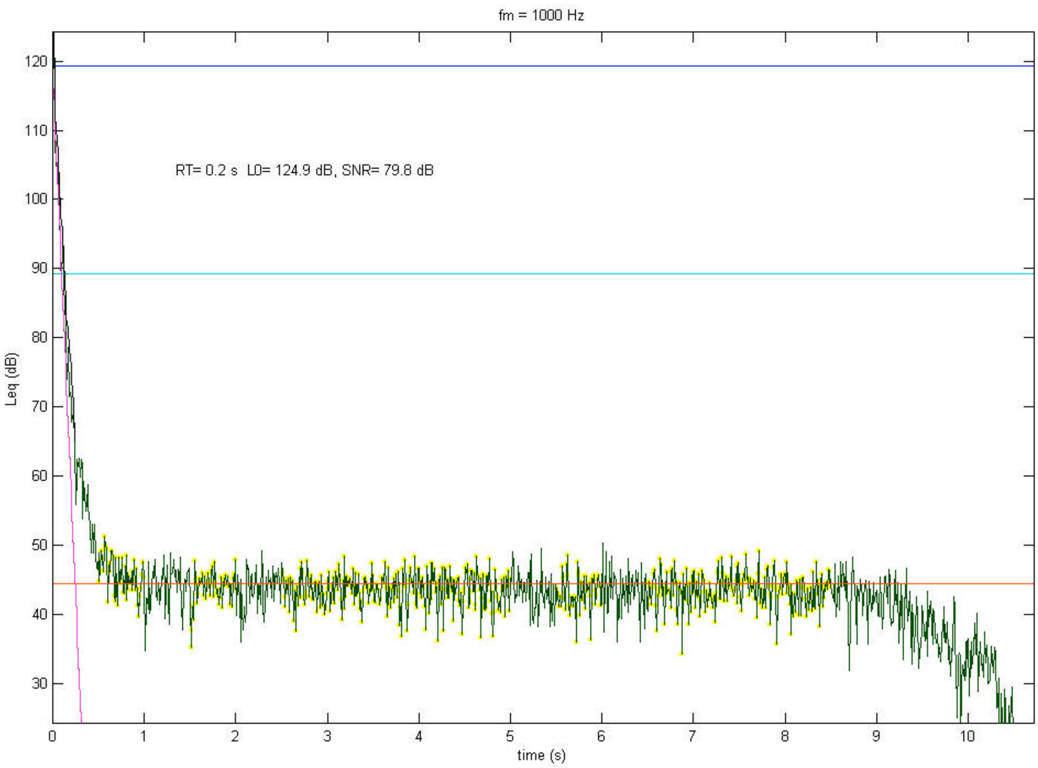

Fig. 3 *Impulse response measured with sine sweep technique*

Figure 3 shows an example of a result obtained by the sine sweep based measurement in the 1000 Hz third-octave band. Length of measured impulse response exceeds 10 s and the measured SNR is 79.8 dB. The level and reverberation time is calculated from the response. The estimated reverberation time for 30 dB dynamic range is indicated by a straight line.

6. CONCLUDING REMARKS

Use of sine sweep technique in building and room acoustics measurements relieves the user from the weaknesses present with MLS measurements. Comparison of the two techniques, presented here, shows unambiguously the superiority of the sine sweep method. The main upside of MLS method is its computational simplicity. However, as computational power in a modern sound level meter allows implementation of the sine sweep, the value of this upside is today strongly reduced.

Fig. 4 *Sound analyser Nor121 may be equipped with the sine sweep option.*

7. REFERENCES

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[4] ISO/FDIS 3382 Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters