Influence of Loudspeaker Distortion on Room Acoustic Parameters

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Introduction

The assessment of the range of uncertainty for room acoustic parameters is an ongoing research topic. ISO 3382 demands the calculation of the uncertainty according to the GUM. However, the separation and determination of the main influence factors and their contribution is still not fully solved. Mainly the position of the sound source and the microphones, [1, 2, 3] background noise [4, 5, 6] and the loudspeaker directivity pattern [7] are currently addressed due to strong deviations observed in the past. In this contribution we explain an existing modeling technique of non-linear systems that is used to simulate the effect of loudspeaker distortion in impulse response measurements. Generic impulse responses are used to simulate a room acoustic measurement. We will analyze which room acoustic parameters are potentially affected. The evaluation of the room acoustic parameters leads to a scenario with controllable degree of loudspeaker distortion without the influence of the other uncertainty factors priorly addressed. This simulation approach is validated by measurement results with different amplifications in auditoria using exponential sweep measurements.

Emulation of Measurement Chain

The approach in this paper uses the open source ITA-Toolbox for MATLAB (www.ita-toolbox.org) [8] including the additional open-source applications *measurement* and the *roomacoustics*. The block diagram used for the emulation of the measurement chain is depicted in Figure 1. In this work quantization and noise are switched off to analyze the influence of nonlinearities separately. Nonlinearities are assumed to be added mainly by the loudspeaker and hence the nonlinear model block is introduced prior to the linear room acoustic transfer function.

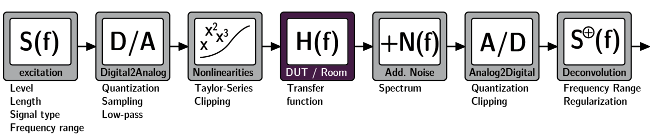

Figure 1: Block diagram used to emulate the measurement chain including quantization, sampling, linear transfer characteristics $H(f)$ and simple polynomial nonlinear model.

The impulse response or transfer function $H(f)$ for the ongoing uncertainty analysis is taken from an analytic model for rectangular rooms with rigid boundaries as described in [9]. This approach allows for arbitrary decays and noiseless input data. The ideal impulse response used in this paper is shown in Figure 2. The room was chosen with dimensions $8 \times 5 \times 3$ meters. A mean reverberation time of 1 s was used to calculate the modal damping constants. The maximum frequency was set to 4 kHz.

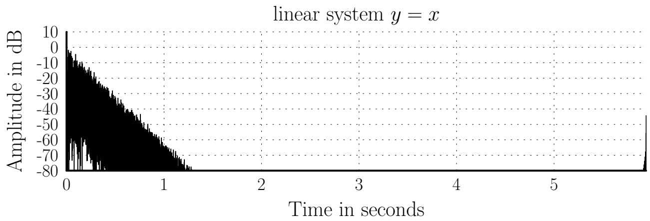

Figure 2: Ideal impulse response obtained by modal superposition with a simple analytic model for rectangular rooms used in the emulation of the measurement chain.

Modeled Loudspeaker Nonlinearities

As electrodynamic loudspeakers are known to show nonlinear behavior if driven with relatively high input voltages [10], the loudspeaker is approximated by a simple polynomial nonlinear model as proposed by Novak [11] and also published slightly different in [12]. It has been proven that sweep measurements are not able to suppress artefects caused by nonlinearites in general [13]. Especially odd ordes can severely influence the impulse response that can be obtained after applying a time window to suppress harmonic impulse repsonses [14].

The model can be simply written in a continuous manner for the output signal $g(t)$ depending on the input singal $s(t)$ and the polynomial coefficients c_k for the order k as:

$$g(t) = \sum_{k} = c_k \cdot s^k(t) \,. \qquad (1)$$

Due to the necessary time-discretization in computer programm the Nyquist theorem has to be considered for $k > 1$. Hence, the discrete time signal cannot be e.g. squared sample wise. A proper low-pass filter or a combination of oversampling, exponentiation and downsampling has to be used instead to avoid aliasing artefacts.

In order to study the influence of even and odd orders independently the two polynoms $g(t)_{\text{even}} = s(t) + s^2(t)$ and $g(t)_{\text{odd}} = s(t) + s^3(t)$. Higher orders are not used in this work as this would not add more information for the demonstration of the artefacts. Since we concentrate on sweep measurements two different artefacts are expected for the even and odd orders. The *input-output-diagram* for both polynoms is depicted in Figure 3. For the level of 0 dBFS the linear and the non-linear parts have the same energy. This is chosen as a worst case scenario. Experienced operators investigate the level of total harmonic distortion that is typically far below 10 %.

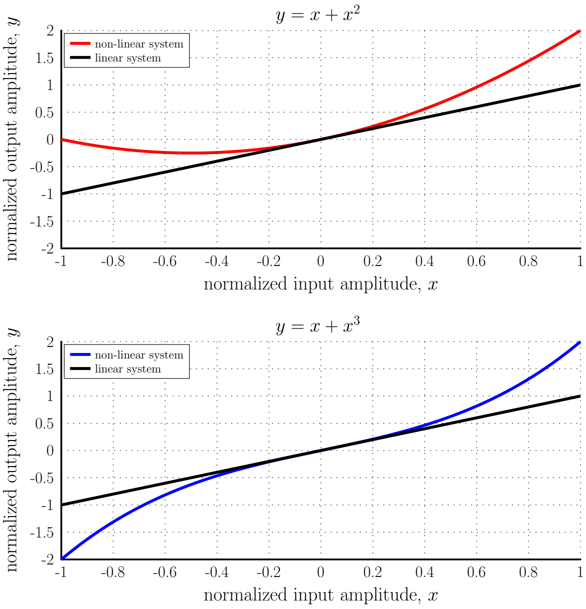

Figure 3: Input-output-diagram for $g\,(t)_{\text{even}}$ and $g\,(t)_{\text{odd}}$ used as two simple non-linear models.

Overlapping Harmonics — All orders

The harmonic impulse responses appear prior to the fundamental impulse response. The time Δt_k between the fundamental impulse response and the harmonic k is given as

$$\Delta t_k = \frac{\log_2(k)}{r_s}, \tag{2}$$

where r_s is the sweep rate for exponential sweeps that represents the frequency range of the sweep in octaves normalized to the signal length in seconds. Details on the time shift and an explaination that the harmonics impulse responses are also shifted in phase can be found e.g. in [14, 15, 16, 17].

In case the time for the second harmonic t_k is smaller than approx. the reverberation time this second harmonic overlaps with the fundamental impulse response, that carries the information. We chose the sweep rate in a way that the second harmonic (even order) partly overlaps with the fundamental impulse response but the third harmonic (odd order) does not. Hence, the influence due to this overlapping can be studied by varying the amplitude of the excitation signal (e.g. sweep). For increasing amplitudes the second harmonic will increase in relation to the fundamental impulse response.

Deviation in Fundemantal — Odd orders

As already published by TORRAS-ROSELL ET AL. in [13] the fundamental impulse response is influenced by odd polynomial orders. This can be shortly explained by the fact that a polynom $g(t) = s^3(t)$ will respond to a sine with specific frequency at the input with two sines at the output—one with the same frequency and one with three times the frequency. The same behavior can than be found for sweeps. As long as the level is kept constant between two measurements the fundemental will not change [18]. By using the odd order polynom $g_{\text{odd}}(t)$ this effect can be modeled with a variation of the driving amplitude at the input of the non-linear model as well.

Simulation Results

Simulations with the simple non-linear model using both polynoms are carried out. The driving amplitude of the sweep called—*output amplification* in the following—is increased step-wise to increase the influence of the non-linearities. The length of the sweep was approx. 4 s followed by a silence of 2 s. The sampling rate was 44100 Hz and the frequency range of the sweep was 100 Hz to 16 kHz. Hence, the sweep rate was 1.9 oct./s.

The resulting impulse response obtained by the emulated measurement for the even order polynom is shown in Figure 4. As can be seen, the deviation compared to the ideal impulse reponse due to overlapping in the beginning of the simulated impulse response is approx. 40 dB below the level of the ideal impulse reponse. Due to the small deviation only small deviations of the room acoustic parameters are to be expected.

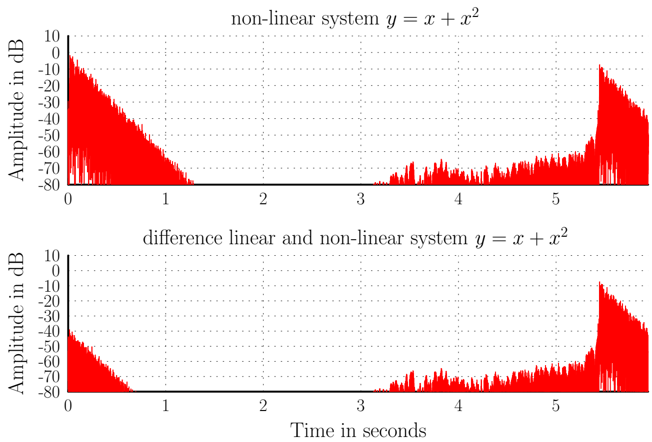

Figure 4: Simulation of impulse response with emulated measurement chain using the non-linear model $g\,(t)_{\text{even}}$ (top) and deviation from ideal impulse response

The error in the room acoustic parameters due to a more and more overlapping second harmonic is depicted in Figure 5 for the early decay time and the clarity index. Figure 6 shows the error in the sound strength including the simulated impulse resonse and the error due to a simple change in level of the fundamental without using the impulse response in the emulated measurement chain. Due to the overlapping, errors in the room acoustic parameters can be observed. As mentioned earlier the energy of the overlapping harmonic had 40 dB less energy than the fundamental. Hence, the sweep rate should be always chosen to avoid such overlapping as the errors are already in the same order of magnitude as the *just noticeble difference* of approx. 5 % for reverberation times and 1 dB for the clarity index [19]. In case, without the impulse response no error in gain is theoretically expected.

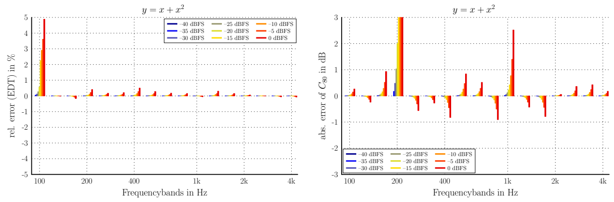

Figure 5: Error in the room acoustic parameters EDT (left) and C_{80} (right) for different levels of the excitation signal and even order polynom.

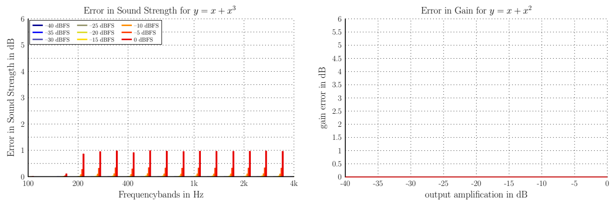

Figure 6: Error in the room acoustic parameter sound strength G (left) and theoretical error due to level change (right) for different levels of the excitation signal and even order polynom.

For the odd orders, the impulse response of the third harmonic can be clearly seen in the end of the impulse response in Figure 7. But more interestingly, the fundamental impulse response has also changed as can be seen in the difference plot. The level of the deviation is almost as high as the ideal impulse response itself. Hence, errors in the room acoustic parameters might occur.

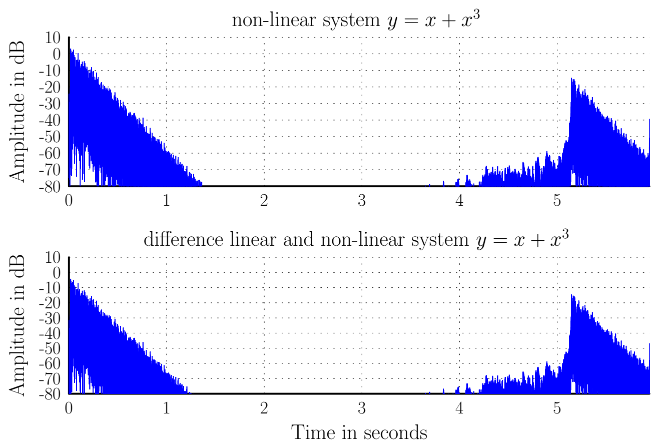

Figure 7: Simulation of impulse response with emulated measurement chain using the non-linear model $g(t)_{\text{odd}}$ (top) and deviation from ideal impulse response (bottom)

The room acoustic parameters EDT and C_{80} are shown in Figure 8 in the same manner as for the even order. The errors are much smaller than for the even order polynom as almost no overlapping occurs. The error in sound strength is shown in Figure 9.

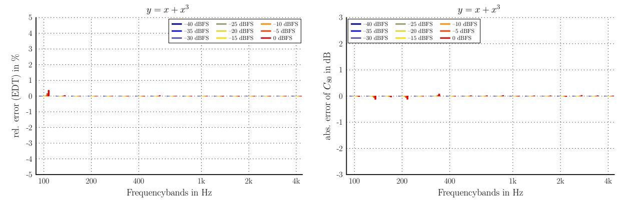

Figure 8: Error in the room acoustic parameters EDT (left) and C_{80} (right) for different levels of the excitation signal and odd order polynom.

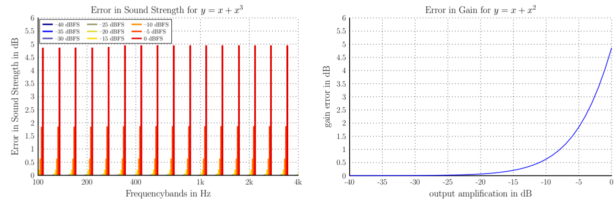

Figure 9: Error in the room acoustic parameter sound strength G (left) and theoretical error due to level change (right) for different levels of the excitation signal and odd order polynom.

Measurement Results

A measurement was carried out in the large auditorium *Aula I* at RWTH Aachen University at several positions. The mid-frequency loudspeaker of the three-way dodecahedron loudspeaker developed by ITA was used. The ITA-Toolbox with MATLAB was used for the measurements. During these measurements the dependency of the parameter sound strength was observed first and the investigation using the nonlinear model followed.

Figure 10 shows the observed dependence of the sound strength due to a change of amplification level. The actual change of the level is compensated for during the measurement. The observed deviation might therefore be due to a nonlinear element in the measurement chain, which is assumed to be the loudspeaker.

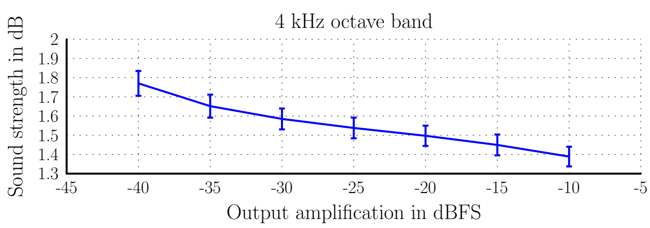

Figure 10: Measured dependence of the sound strength due to a change of amplification level.

Conclusion

A complete emulation of a measurement chain including nonlinearities has been implemented in MATLAB with the ITA-Toolbox and is freely available. This emulation uses a simple polynomial non-linear model. It was used to analyze uncertainties firstly observed in the measurement of the room acoustic parameter sound strength. The influences of nonlinearities on the impulse response and hence on the room acoustic parameters were studied for even and odd orders separately for exponential sweep measurements. [1] Even and odd orders of the non-linear model show different effects. Odd orders influence the fundamental impulse response. Even orders were used to control the overlap of harmonic impulse responses in sweep measurements with the fundamental. The reverberation time and also the relative energy parameters e.g. clarity or definition, are not really affected by the frequency independent non-linearies of odd polynomial order but of even order due to this overlapping. Sweep parameters should be chosen carefully to avoid possible overlapping as the errors in the studied example were already in the same order of magnitude as the just noticable difference for these parameters.

The parameter sound strength is subject to a calibration measurement and the fundamental impulse response of loudspeaker might deviate in the calibration measurement in free-field and the actual measurement in the room, due to level changes as observed in the measurement. The emulation of the measurement chain was able to simulate this behavior. Besides the influence of the overlapping this parameter is in contrary to the relative parameters very sensitive to odd polynomial orders. Uncertainties in e.g. lateral fraction due to such non-linearities are not expected by the authors as always two microphone signals are compared that originate from the same loudspeaker with the same amplitude and hence the same non-linearities. However, a simulation should be studied in future.

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References

[1] J. Davy, "The relative variance of the transmission function of a reverberation room," *Journal of Sound and Vibration (JSV)*, vol. 77, no. 4, pp. 455–479, 1981.

[2] D. de Vries, E. M. Hulsebos, and J. Baan, "Spatial fluctuations in measures for spaciousness," *Journal of Acoustical Society of America*, vol. 110, pp. 947–954, August 2001.

[3] I. Witew, P. Dietrich, S. Pelzer, and M. Vorländer, "Comparison of different modelling strategies to predict the spatial fluctuation of room acoustic single number quantities," in *40th Italian (AIA) Annual Conference on Acoustics and the 39th German Annual Conference on Acoustics (DAGA)*, 2013.

[4] A. Lundeby, T. E. Vigran, H. Bietz, and M. Vorlander, "Uncertainties of measurements in room acoustics," *Acta Acustica united with Acustica*, vol. 81, no. 4, pp. 344–355, 1995.

[1] Uncertainties due to nonlinearities in MLS are not focus of this manuscript but might be investigated with the simulation script for data presented included in the ITA-Toolbox. `ita_tutorial_nonlinearDAGA2013.m`

[5] M. Guski, P. Dietrich, and M. Vorländer, "Positionsbedingte Unsicherheiten raumakustischer Parameter für geringe Modendichten anhand eines Reckteckraummodells," in *38th German Annual Conference on Acoustics (DAGA)*, Darmstadt, Germany, March 2012.

[6] M. Guski and M. Vorländer, "Measurement uncertainties of reverberation time caused by noise," in *40th Italian (AIA) Annual Conference on Acoustics and the 39th German Annual Conference on Acoustics (DAGA)*, 2013.

[7] R. S. Martin, I. Witew, M. Arana, and M. Vorlander, "Influence of the source orientation on the measurement of acoustic parameters," *Acta acustica united with acustica*, vol. 93, no. 3, pp. 387–397, 2007.

[8] P. Dietrich, M. Guski, J. Klein, M. Müller-Trapet, M. Pollow, R. Scharrer, and M. Vorländer, "Measurements and room acoustic analysis with the ita-toolbox for matlab," in *40th Italian (AIA) Annual Conference on Acoustics and the 39th German Annual Conference on Acoustics (DAGA)*, 2013.

[9] M. Pollow, P. Dietrich, and M. Vorländer, "Room impulse responses of rectangular rooms for sources and receivers of arbitrary directivity," in *40th Italian (AIA) Annual Conference on Acoustics and the 39th German Annual Conference on Acoustics (DAGA)*, 2013.

[10] W. Klippel, "Nonlinear large-signal behavior of electrodynamic loudspeakers at low frequencies," *Journal of the Audio Engineering Society (JAES)*, vol. 40, no. 6, pp. 483–496, 1992.

[11] A. Novak, "Identification of nonlinear systems in acoustics," PhD Thesis, Universite du Maine, Le Mans, France, 2009.

[12] L. Tronchin, "The emulation and of nonlinear and time-invariant audio and systems with memory and by means and of volterra and series," *Journal of the Audio Engineering Society (JAES)*, vol. 60, no. 12, pp. 984–996, 2012.

[13] A. Torras-Rosell and F. Jacobsen, "A new and interpretation of distortion and artifacts in sweep and measurements," *Journal of the Audio Engineering Society (JAES)*, vol. 59, no. 5, pp. 283–289, May 2011.

[14] S. Müller and P. Massarani, "Transfer-function measurement with sweeps," *Journal of the Audio Engineering Society (JAES)*, vol. 49, pp. 443–471, 2001, printed.

[15] A. Farina, "Advancements in impulse response measurements by sine sweeps," in *AES 122nd Convention*, vol. 122, Vienna, Austria, 2007.

[16] A. Farina, "Simultaneous measurement of impulse response and distortion withaswept-sinetechnique," 2000, pp. 18–22.

[17] P. Dietrich, B. Masiero, and M. Vorländer, "On the optimization of the multiple exponential sweep method," *Journal of the Audio Engineering Society (JAES)*, (2013), submitted.

[18] S. Müller and P. Massarani, "distortion immunity in impulse response measurements with sweeps," in *ICSV 18*, 2011.

[19] ISO, *Acoustics – Measurement of Room Acoustic Parameters – Part 1*, ISO Std., 2009.