Input-Output Linearization of a MEMS Loudspeaker Using a Hammerstein Model

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Introduction

Micro-electro-mechanical systems (MEMS) based acoustic transducers are of high interest for in-ear-applications such as hearables and hearing aids. This is because the MEMS concept offers the potential to build small-scale low-cost transducers with high sound pressure levels (SPL) and low power consumption [1] which are moreover suitable for batch manufacturing. Furthermore the technology can be coupled with the driving electronics, such as amplifiers and signal processing units, without the need to leave the MEMS manufacturing process.

One problem with microspeakers in general is the level of nonlinear distortion when high SPL is required. In such situations, it is necessary to compensate for this distortion. For loudspeakers, where no output signal is available, it is appropriate to apply a prefilter (so-called predistorter) to the input signal. The characteristics of the predistorter cascaded with the nonlinear system should be such that the dynamic of this whole system is ideally equivalent to that of a linear system. The predistortion acts as the direct inverse of the nonlinearities of the speaker. This approach is called input-output linearization.

This paper explores a linearization of an electrostatic driven MEMS transducer with a feedforward controller based on a relatively simple block structured nonlinear model.

MEMS-based Speaker

The MEMS-based speaker under investigation, schematically shown in Figure 1, is an all-silicon CMOS compatible device which comprises multiple identical nanoscopic electrostatic drive (NED) actuators [2]. Such actuators work based on the electrostatic principle. Here, an alternating electrical potential is set between two electrodes by applying a reasonably high voltage. The resulting electrical field creates a force, the Coulomb force, that attracts or repels the electrodes. It causes the air between electrodes to move, creating sound waves. The NED enables a reduction of the needed voltage, but comes with the cost of a "rather complex" design [1, 3]. Here small gap sizes are combined with the possibility of high excursions and relative large air volume displacements. The NED principle relies on a transformation of forces that is combined with a lever mechanism. The resulting deflection can then be greater than the electrode gap itself. A combination of a large number of these beams results in a reasonably high SPL [3].

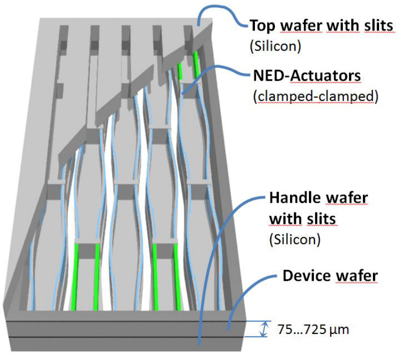

Figure 1: NED microspeaker with multiple actuators and the top and bottom (handle) wafer with vents. The beams are shown in the deflected state.

Measurement procedures for these microspeakers are a difficult task and need specialized equipment. Especially electrical and mechanical measurements need special care, since the membranes (i.e. beams) are capsuled and the occurring currents are very small. This fact and the complex underlying structure makes the building of an exact physical model, e.g. for the purpose of linearization and control, a difficult, error prone and time consuming task. Therefore, a data driven modeling approach, based only on acoustical measurements is expected to circumvent some of these problems.

Model Structure

Various methods can be used to identify nonlinear systems, such as:

- Volterra series models,
- Block structured models,
- State-space models,
- Neural Network models,
- etc.

Due to the novelty of the MEMS speaker and the complexity of its structure, its description in the state space with sufficient accuracy is an extremely challenging task. The use of Volterra series and neural networks can lead to an overcomplicated model with great number of parameters [4]. In connection with the foregoing, it was decided to use a simple block structured model. Models of this type were used for loudspeaker linearization before and could yield promising results [5].

In this paper, a Hammerstein model is used to describe the nonlinear behavior of the microspeaker. Figure 2 shows the block diagram of this model.

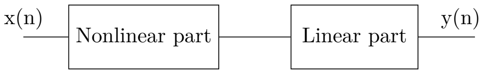

Figure 2: Structure of Hammerstein model

The Hammerstein structure consists of a static nonlinear block at the input in series with a linear block. A fourth-order polynomial was chosen for the nonlinear part of the Hammerstein model:

$$f(x(n)) = c_0 + c_1 x(n) + c_2 x^2(n) + c_3 x^3(n) + c_4 x^4(n), \quad (1)$$

where c_i are the polynomial coefficients. For the linear part a 32-tap FIR filter delivered promising results:

$$y(n) = b_0 f(x(n)) + ... + b_{31} f(x(n-31)), \quad (2)$$

with b_i being the FIR filter coefficients. Hence, the model of the microspeaker is described by the following vector of 37 parameters:

$$\mathbf{p} = [p_0, p_1, ..., p_{36}] = [c_0, c_1, ..., c_4, b_0, b_1, ..., b_{31}]. \quad (3)$$

Model Parameter Estimation

To search for the model parameters, measured speaker data was used. Separate sinusoidal signals, as well as combinations of two sinusoidal signals at different frequencies, were used as test signals. The output signal of the MEMS speaker was recorded from the handle wafer side (s. Figure 1) with a GRAS RA0401 ear simulator (in accordance with IEC 60318-4) directly mounted on the circuit board in an air-tight fashion. The ear simulator was used with a Microtech Gefell MV203 preamp and a GRAS 12AQ power module, followed by a Lynx Hilo for analog-to-digital conversion. A Bias voltage of 40 V_{DC} and a signal voltage of 5 V_{AC} were provided by a PiezoDrive PX200 amplifier.

A problem of using these measurements for model parameter estimation was the lack of synchronization between the input and output signals, which did not allow their consideration in the time domain. Therefore, a transformation to the frequency domain of the measured data was performed.

For the parameter estimation a combination of a genetic algorithm and the Nelder-Mead method were used [6, 7]. The Genetic algorithm searches for a coarse global minimum of the fitness function. The Nelder-Mead method is used for an additional fine-tuning. As fitness function for the optimization, the mean absolute error between the model and the loudspeaker amplitude frequency function in the range of 20 Hz to 20 kHz was used:

$$F(\mathbf{p}) = \frac{\sum\limits_{n=1}^{N} |\hat{f}_{mesured}(n) - \hat{f}_{\mathbf{p},model}(n)|}{N} \mapsto min, \quad (4)$$

where $F(\mathbf{p})$ is the fitness function, $\mathbf{p}$ is the vector composed of the nonlinear and linear model parameters, $\hat{f}_{mesured}$ is the amplitude frequency response of the measurement and $\hat{f}_{\mathbf{p},model}$ is the amplitude frequency characteristic of the model output with given model parameters $\mathbf{p}$, N is the total number of frequency samples. A comparison of the speaker measurements and the model output is shown in Figure 3 and Figure 4. Here the amplitude frequency is plotted for two different test signals, i.e. a sinusoid with 880 Hz and a mixture of two sinusoids, one with 300 Hz and one with 1300 Hz. One can see that the model mimics the behavior of the speaker quite well, with just a small deviation in the amplitude of the sinusoids.

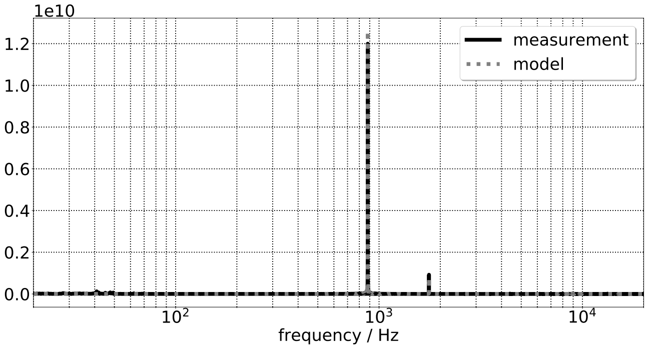

Figure 3: The output of the measurements of the MEMS speaker and the model with a sinusoidal signal at 880 Hz as input.

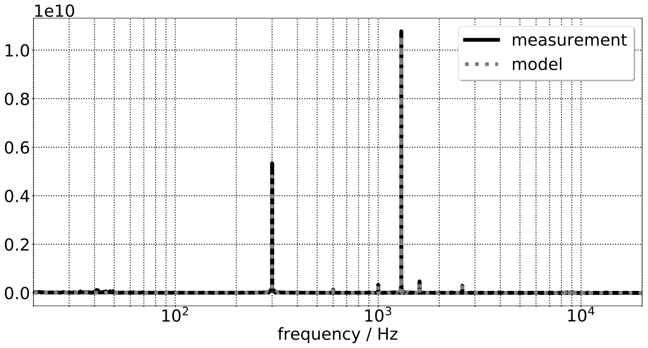

Figure 4: Speaker and model amplitude frequency characteristic on combination of 2 sinusoidal signals at 300 Hz and 1300 Hz.

Nonlinear Distortion Suppression

The problem of suppressing nonlinear distortion is solved by using a filter, which is the inverse of the nonlinear part of the Hammerstein model. In the general case, searching for an inversion of a fourth-order polynomial is a nontrivial task. Here, in order to find the roots of the model polynomial, the Newton's method is used [8]. By this, the required predistortion of the input data stream can be achieved.

In order to evaluate if the linearization with the proposed method is working properly, the THD and IMD of the MEMS transducer were measured. In [3] it was shown that mostly second order products contribute to the nonlinear behavior of the MEMS transducer, both

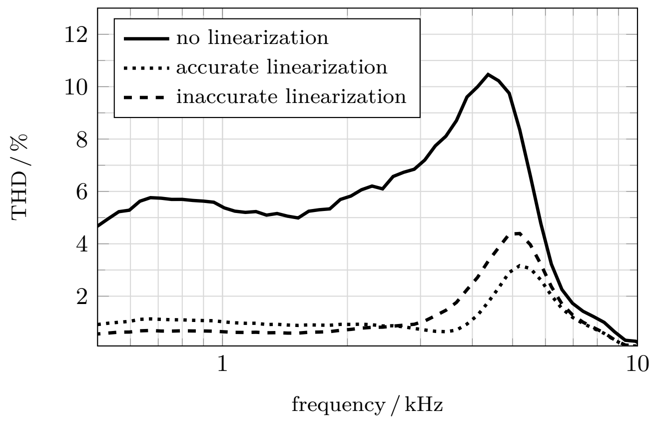

Figure 5: Measured THD at 40 $\mathrm{V_{DC}}$ and 5 $\mathrm{V_{pp,\ AC}}$ of the NED MEMS transducer with and without linearization. The measurements were performed in a GRAS RA0401 ear simulator.

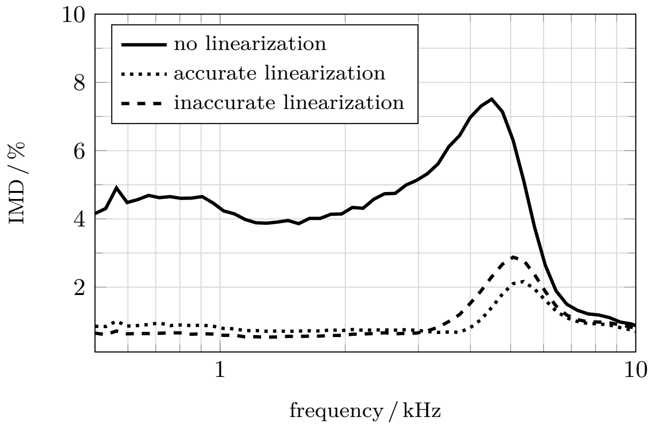

Figure 6: Measured IMD at 40 $\mathrm{V_{DC}}$ and 5 $\mathrm{V_{pp,\ AC}}$ of the NED MEMS transducer with and without linearization. The measurements were performed in a GRAS RA0401 ear simulator.

for THD and IMD. For this reason only the total curves are shown in the resulting plots.

For the evaluation the measurements were performed as above. The THD and IMD were measured based on IEEE 1241 and ITU-R SM.1446 respectively. As input signals for these measurements, prefiltered test signals were used. The measurements were performed for three different cases. In the first case (no linearization) the test signals were not filtered at all to get the raw THD and IMD. In the second case (accurate linearization), the applied predistortion was based on an accurately fitted model. For the third case (inaccurate linearization), the model was fitted to a different sample of the NED MEMS speaker. This should clarify if the proposed linearization method can be applied universally for all NED MEMS speakers, or if different models or closed loop control solutions should be applied.

The results of the measurements are shown in Figure 5 for THD and Figure 6 for IMD. The linearization achieves a reduction of the THD and IMD by around 69 % and 71 % respectively, at the corresponding maximum values. What looks like a shift of the maximum on the frequency axis is assumed to be a lower reduction of THD and IMD at these Y. It is also clear that the linearization cannot achieve its optimal performance, if the underlying model is not fitted properly to the present MEMS speaker. This implies that parameter drifts due to aging or manufacturing tolerances need to be considered, e.g. by different models or adaptive, closed loop strategies.

Conclusion

This paper presented a linearization approach to an electrostatic MEMS speaker that inhibits some nonlinear distortion. This distortion could be lowered by a rather simple approach, that is based on a data-driven modeling process. By this the cost of complicated and time consuming measurements, for building an exact physical model could be overcome. It was shown that the used method could reduce the THD and IMD distortion by a great amount. Furthermore the results show, that more sophisticated adaptive control strategies may be needed, to account for manufacturing tolerances.

Besides this, the future work will focus on applying more complex structured models. It is also conceivable, to incorporate prior knowledge of the speakers physics and structure into the block oriented model.

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