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High-Fidelity Modeling of Harmonic Distortions in Piezoelectric MEMS Microphones with a Corrugated Membrane

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Summary:

We present a high-fidelity, computationally efficient approach for modeling harmonic distortions in piezoelectric MEMS microphones featuring a fully-clamped corrugated membrane design. The described method correctly predicts the total harmonic distortion (THD) of two manufactured design variants, thereby paving the way for THD optimization throughout the design process. Remarkably, one of the design variants shows a THD of 1% at a very high sound pressure level (SPL) of $130\ \mathrm{dB_{SPL}}$, thus outperforming commercially available piezoelectric and capacitive single-backplate (SBP) microphones.

Keywords: Piezoelectric MEMS Microphone, Corrugated Membrane, Total Harmonic Distortion

Introduction

Capacitive MEMS microphones currently set the benchmark in technology due to their superior acoustic performance and compatibility with well-established semiconductor fabrication processes. However, unlike their capacitive counterparts, piezoelectric MEMS microphones do not require a bias voltage, which makes them a compelling choice for applications that require low-power consumption. Furthermore, capacitive microphones that utilize constant-charge readout are inherently nonlinear. This is attributed to the presence of parasitic capacitances and the nonlinear electrostatic force acting between the membrane and backplate [1].

Recently, a novel design of a piezoelectric MEMS microphone was proposed that leverages a fully-clamped corrugated membrane (see Fig. 1a) [2]. The corrugations release residual material stress to achieve a sufficiently compliant membrane and result in a spatial separation of tensile and compressive regions upon acoustical loading. This pseudo-bimorph design enables a single-ended or differential readout without requiring an intermediate electrode. Here, the THD of two corrugated membrane designs is investigated and a simulation method is proposed.

Materials and methods

A microphone can be considered as a system with pressure input $p_{\mathrm{in}}(t)$ and voltage output $V_{\mathrm{out}}(t)$ related by a function σ:

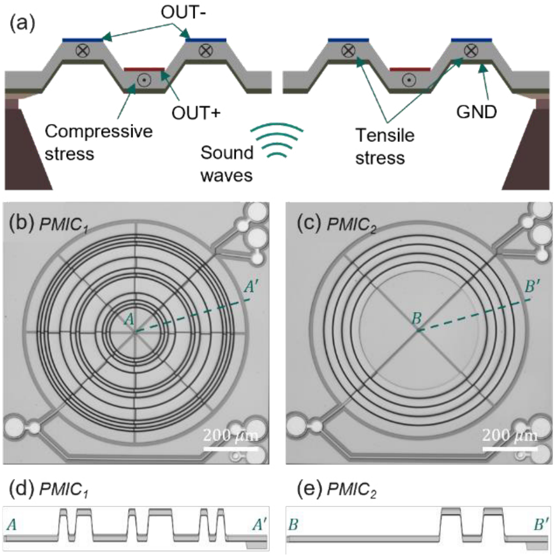

Fig 1. (a) Schematic of a corrugated membrane with electrodes OUT+, OUT- and GND. (b), (c) Optical microscopy images and (d), (e) rotational-symmetric cross-sections of two manufactured design variants.

$$V_{\mathrm{out}}(t) = \sigma(p_{\mathrm{in}}(t)) \tag{1}$$

To quantify the THD, the microphone is loaded with an input signal $p_{\mathrm{in}}(t) = \hat{p}\sin(2\pi f t)$ with amplitude $\hat{p}$ and frequency $f = 1\ \mathrm{kHz}$. In the microphone's linear regime, the output is a sinusoidal signal of the same frequency, where the output voltage linearly follows the input pressure. However, nonlinearities can result in higher-order harmonics in the output signal. To model this behavior, σ is expressed as a polynomial function, i.e., $\sigma_{\text{poly}}(p_{\text{in}}) = a_n p_{\text{in}}^n + a_{n-1} p_{\text{in}}^{n-1} + \cdots + a_0$, for which $V_{\text{out}}(t)$ consequently becomes a finite Fourier series:

$$V_{\text{out}}(t) = V_0 + \sum_{i=1}^{n} V_i \sin(2\pi i f t + \varphi_i) \qquad (2)$$

The THD is then calculated as the contribution of higher modes in the output signal (up to order $n = 5$ is sufficient) to the linear response V1:

$$\text{THD} = \sqrt{\sum_{i=2}^{5} V_i^2} / V_1 \qquad (3)$$

To this end, the output signal $V_{\text{out}}(t)$ obtained from transient FEM simulations is decomposed into harmonics through Fourier transformation according to eq. (2). However, this is computational expensive and not well suited for optimization studies as the THD is usually of interest for a wider range of input pressures.

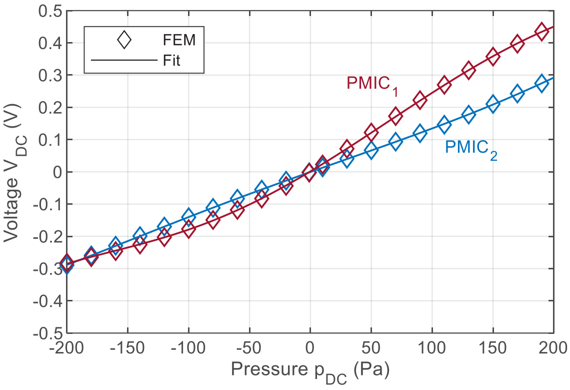

Fig 2. Nonlinear static response obtained from FEM and polynomial fit for the variants PMIC₁ and PMIC₂.

Alternatively, the nonlinear static response V_{DC} can be simulated for a wide range of input pressure values p_{DC}, which is much faster than the transient simulations. Subsequently, a polynomial function is fitted to the simulated static response, i.e. $V_{\text{DC}} \approx \sigma_{\text{poly}}(p_{\text{DC}})$, from which the transient response is obtained as $V_{\text{out}}(t) = \sigma_{\text{poly}}(\hat{p}\sin(2\pi f t))$. Finally, a Fourier transform is applied and the THD can be calculated from eq. (3). A prerequisite for this method is that the response at the frequency of interest, i.e., $1\,\text{kHz}$, equals the static response. This is fulfilled as the low frequency roll-off is not included in the FEM simulations and the frequency response is flat within the audio band ($20\,\text{Hz}$ to $20\,\text{kHz}$).

Results

The simulated nonlinear static response is shown in Fig. 2 for both design variants depicted in Fig. 1. Variant PMIC_1 exhibits strong asymmetries w.r.t the unloaded state ($p_{\text{DC}} = 0$) as well as clipping behavior for higher pressures. These nonlinearities are significantly reduced for PMIC_2 indicating the potential of THD optimization by tuning the positions and numbers of corrugations. By decomposing the THD into even and odd harmonic distortions, i.e., HD_{even} and HD_{odd}, which represent asymmetries and clipping behavior respectively, the contributions of the total THD can be quantified as shown in Tab 1.

Tab. 1: Simulated harmonic distortions at $130\ dB_{SPL}$

Variant	HD_{even} (%)	HD_{odd} (%)	THD (%)
$\mathbf{PMIC_1}$	6.70	1.31	6.82
$\mathbf{PMIC_2}$	0.85	0.51	0.99

Finally, the THD is simulated for multiple input pressures and compared with experimental measurements as well as two commercial microphones (see Fig. 3). This shows excellent agreement between measurement and simulation and demonstrates that the 1%-THD of PMIC_1 is superior to both reference microphones.

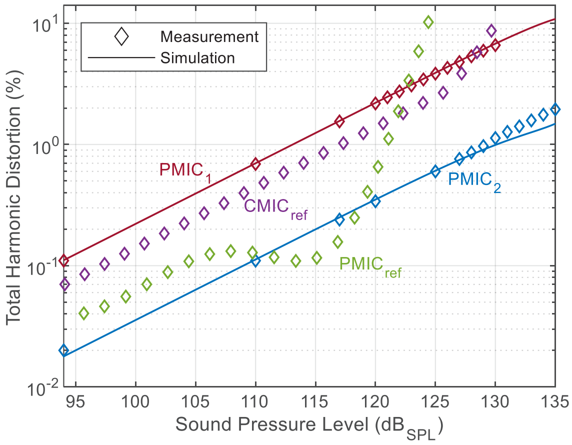

Fig 3. Measured and simulated THD for the variants PMIC₁ and PMIC₂. The THDs for the SOTA commercially available piezoelectric PMICref and capacitive reference microphone CMICref (Infineon IM68A130) are extracted from the respective datasheets.

Conclusion

We presented a fast and highly accurate method to simulate the THD of MEMS microphones enabling the optimization of the THD in the design phase. The investigation of two novel piezoelectric corrugated membrane-based designs revealed that the THD of the devices can be substantially reduced by adjusting the corrugations and is superior to state-of-the-art devices.

References

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