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Optimization of Harmonic Distortions for Electrostatic MEMS Push-Pull NED-Microspeakers

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Summary:

Electrostatic actuators realizing the push-pull principle enable a MEMS-based microspeaker with the perspective of a power efficient CMOS-compatible and RoHs compliant sound transducer for in-ear applications. Each clamped-free actuator is placed within its own cavity. A periodic oscillation of an actuator ensemble generates the sound signal. Combining a differential drive with two independent actuator layers ideally allows an actuation without even harmonic distortions. Further, various combinations of signal and bias voltages result in the same sound pressure level (Iso-SPL), leading to the question, how to choose the working point from the perspective of high fidelity. Based on a previous distortion analysis of the voltage scaling, a reduced order model is scaled to reproduce not only distortions but also the experimentally observed pressure signal. Further, Iso-SPL working points are evaluated numerically. Close to the pull-in voltage, above which no stable equilibrium between elastic and electrostatic forces exist, harmonic distortions become from a product point of view unacceptable. Distortions can be minimized for voltage combinations with the same fundamental response, by optimizing the distance not only towards the DC induced pull-in but also towards the quasi-static AC pull-in.

Keywords: MEMS, microspeaker, push-pull, harmonic distortions

High fidelity is a key property of loudspeakers in terms of their quality [1]. Reproducing sound and music with low total harmonic distortion (THD), namely below 1% [2], is desirable. Non-linear systems generate not only the fundamental amplitude A_1 at the same frequency as the driving voltage signal but also higher harmonic amplitudes A_n. As a figure of merit, the harmonic distortions K_n by a single-tone excitation are often analysed [3] [4],

$$K_n = \frac{A_n}{A_1}. \quad (1)$$

Among various kinds of loudspeaker systems, electrostatic ones are already established for high fidelity applications [5]. Electrostatic loudspeakers can be divided in general into two classes, namely single-sided pull systems with one stator combined with a deflected electrode and balanced systems with two stators loaded by bias voltages with opposite signs combined with a movable electrode between them. While the first type suffers mainly from second harmonic distortions due to the quadratic voltage dependency of the electrostatic force, the balanced one has ideally no even harmonic distortions. Nevertheless, the non-linear force-displacement-connection leads to the generation of odd harmonics in both cases [6]. The miniaturization of in-ear loudspeakers makes the use of MEMS technology interesting. Silicon based solutions combine high scalability with cost efficiency. Thereby, the air-motion principle utilizes the chip volume by arranging multiple actuators within the device plane [7] [8]. Each actuator is surrounded by its own acoustic cavity. By the actuators' periodically oscillation a pressure signal is produced through venting holes in the bottom- and top-layer. The deflection of electrostatic actuators is limited by the pull-in phenomena. If the applied voltage exceeds the pull-in voltage for a voltage-driven system, the electrostatic force is higher than the elastic restoring force. Consequently, the electrodes come suddenly into contact [9]. Without further protection this leads to a short-cut and the device might be destroyed. The pull-in effect also determines the maximum achievable deflection. For instance, for a spring-plate system with a linear spring, the electrode deflection is limited to one third of the gap [9]. Conrad et al. proposed a nano-e-drive (NED) actuator that uses the geometric shape of multiple combined electrodes to translate their movement into a larger deflection for the actuator. This in turn enables small gaps, which are important to maximize the electrostatic driving

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force. Recently, a NED-based microspeaker was proposed for a miniaturized electrostatic push-pull speaker [10] [8]. Compared to an earlier single-sided driven realisation [7], the second harmonic distortion K_2 could be almost completely avoided, leaving the third harmonic distortion K_3 as the main contribution for the total harmonic distortions [8]. This leads to the question of the extent to which the harmonic distortions can be further optimized by selecting the operating point. Here, we start by giving a brief introduction into the order-reduced model (LPM) for the push-pull actuator established in [8] and [11]. Wall et al. suggested a non-destructive electro-acoustic method for the pull-in characterization [11]. In the present paper, this method is extended for the identification of the dimensionless deflection scaling. A numeric analysis of voltage combinations leading to the same sound pressure level forms the basis for optimizing the distortions. Finally, a conclusion is given.

Reduced-order model

Figure 1 displays the several NED-actuators of the microspeaker without the silicon cover. Details about the geometry as well as the fabrication process can be found in [8]. Similar to a bimorph actuator, it consists of two layers, here arranged laterally, that lead to a deflection in opposite directions when actuated.

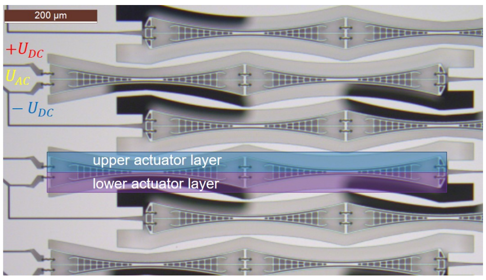

Fig. 1 Top view of the device layer with multiple push-pull NED-actuators with indication of the electrical potentials on one actuator

The dimensionless 1-DOF model equation for this actuator is

$$\frac{\partial^2 a}{\partial \tau^2} + \frac{1}{Q}\frac{\partial a}{\partial \tau} + a = \left(\frac{u_1}{1-a}\right)^2 - \left(\frac{u_2}{1+a}\right)^2 \quad (2)$$

with the deflection a, the quality factor Q, the time τ as well as the voltages u_1 and u_2. Note that all these parameters are dimensionless. The dimensionless voltage u and the voltage U are connected by a scaling with pull-in voltage of the actuator $U_{\mathrm{PI}}(U_{\mathrm{AC}}=0)$:

$$u = \frac{U}{2 \cdot U_{\mathrm{PI}}(U_{\mathrm{AC}}=0)}. \quad (3)$$

The dimensionless deflection a can be scaled to describe the actuator's tip deflection by Θ,

$$a = \frac{x_{\mathrm{Tip}}}{\Theta} \quad (4)$$

in case of a comparison with FEM-simulations of a single actuator [12]. The pressure signal p is related to the fundamental response A_1 of a at the driving frequency by a scaling factor Π,

$$A_1 = \frac{p}{\Pi} \quad (5)$$

and allows a comparison to the measured pressure response of the microloudspeaker. Here, the low-frequency limit is analysed. Thus, the inertia and damping force related to the time derivatives of a are set to zero. The elastic force is modelled linearly due to the clamped-free configuration. For each actuator layer the electrostatic force is modeled as the electrostatic force of a plate capacitor, leading to two terms on the right hand side proportional to the squared voltage for the corresponding layer. This model is equivalent to a spring-plate model with one moveable electrode between two stationary electrodes. A differential drive is utilized for the voltage actuation

$$\begin{aligned} u_1 &= u_{\mathrm{dc}} + u_{\mathrm{ac}}, \\ u_2 &= u_{\mathrm{dc}} - u_{\mathrm{ac}} \end{aligned} \quad (6)$$

with the bias voltage u_{dc} as well as signal voltage $u_s = u_{\mathrm{ac}}\cos(\nu\tau)$ with the frequency ν with $\nu \to 0$ for the low-frequency limit. This driving schema allows the minimization of even harmonics [6] [8].

Non-destructive parameter estimation

Equation (2) reveals only the mathematical structure of the actuator model. A parameter estimation for the voltage as well as deflection scaling is necessary. Using the voltage-deflection-characteristic is questionable, because it is a monotone curve for which both axis are scaled by the parameter estimation. One possible solution is to analyze the third harmonic distortion for a variation of the bias voltage at different constant signal-to-bias voltages, since the harmonic distortions are dimensionless quantities that depend only on the voltage scaling, but not on the deflection scaling [11]. Our approach uses only voltages far below the pull-in and is thus a non-destructive characterisation method. This is particularly important for the push-pull actuator presented here, as it is irreversibly destroyed by the pull-in. Previous investigations, according to the method proposed here, revealed experimentally an effective pull-in voltage and thus voltage scaling in equation (3) of $U_{\mathrm{PI,experiment}}(U_{\mathrm{AC}}=0) = 34.6\,\mathrm{V}$ for a fabricated actuator ensemble [11].

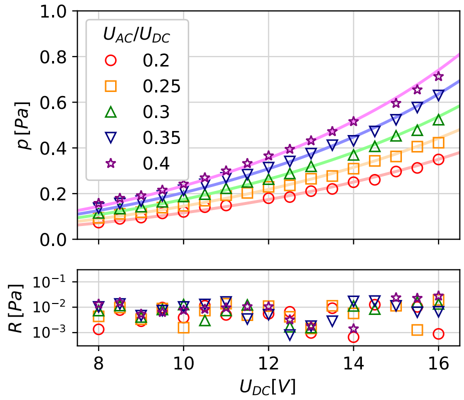

Fig. 2 Measured fundamental pressure signal p at a frequency of $250\,\mathrm{Hz}$ for 70 actuators for a variation of the bias voltage U_{DC} at constant signal-to-bias-ratios with the LPM fit (eq. (2), solid lines) with mit $U_{\mathrm{PI,exp}} = 34.6\,\mathrm{V}$ and $\Pi = 6.32\,\mathrm{Pa}$ as well as the absolute deviation R between measurement and model

In a second step, the scaling of the dimensionless deflection is adjusted by a measurement of the fundamental pressure signal in a 3D-printed closed volume at frequencies far below resonance, for a varied bias voltage at different constant signal-to-bias ratios (see Fig. 2). Therefore, the fundamental response by the LPM is numerically evaluated in the quasi-static limit ($\nu \to 0$). The time-dependent signal voltage is translated point-wise by the voltage-deflection-characteristics of equation (2) without the time derivatives to get the deflection signal. A discrete Fourier transformation based on the Moore-Penrose pseudo inverse yield the fundamental response as well as the harmonic amplitudes. Details about the numerical evaluation as well as the experimental setup can be found in [11]. The parameter estimation (see Fig. 2) reveals that the dimensionless fundamental amplitude A_1 is connected with the fundamental pressure signal p by a constant scaling of $\Pi = 6.32\,\mathrm{Pa}$ (eq. (5)). Thus, a numerical evaluation of A_1 by the LPM (eq. (2)) can be utilized to efficiently evaluate the pressure signal for different working points within the next section.

Results

There is the freedom to choose two voltages for the actuator's driving. For a differential drive, it is the choice of bias and signal voltage. By a numerical evaluation of A_1 (see Fig. 3) it becomes obvious, that different voltage combinations can lead to the same fundamental response. For small voltages the same fundamental amplitude A_1 is generated

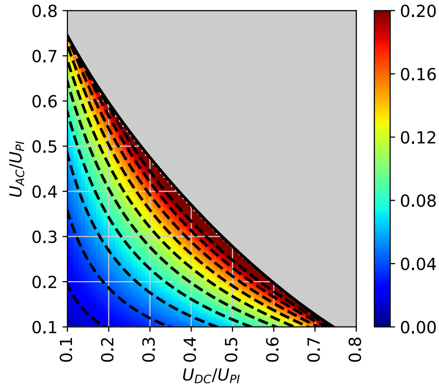

Fig. 3 Voltage combinations with same fundamental amplitude A_1 by a numerical evaluation of equation (2), where regions above the pull-in border (solid line) are grey

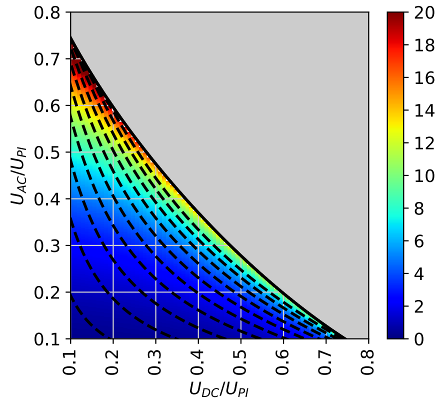

Fig. 4 K_3 in % by a numerical evaluation of equation (2) for different voltage combination with iso-SPL working points as dashed lines

in the case of

$$U_{\mathrm{DC}} \cdot U_{\mathrm{AC}} \approx \mathrm{constant}. \qquad (7)$$

On the other hand, figure 4 displays the numerical evaluation of the third harmonic distortion K_3, according to equation (2). K_3 is the main source of the THD, for various voltage combinations. The voltage dependency differs for A_1 (see Fig. 3) and K_3 (see Fig. 4). Thus, if a voltage combination leads to the same fundamental signal, it can still produce an output of different fidelity. This raises the question of how to optimize the working point.

Figure 5 shows the investigation of iso-SPL working points (see Fig. 3). The voltages are chosen as pairs with the same fundamental response. Consequently, a variation of the bias voltage is accompanied by a change of the signal voltage. It appears, that the optimal choice for the bias voltage is roughly 63% of the pull-in voltage (see Fig. 5 a). The third harmonic distortion is minimal with this setting for various response amplitudes. For the signal voltage, the optimal choice in relation to the pull-in voltage depends on the desired response A_1 (see Fig. 5 b). With regard to the speaker application, this situation turns out to be favorable. A constant bias voltage, which determines the operating point, is supplied by the driving circuit. A music signal and its volume level, on the other hand, are determined by the time-dependent signal voltage. Thus, by setting U_{DC} to roughly 63% of the pull-in voltage, the harmonic distortions can be minimized.

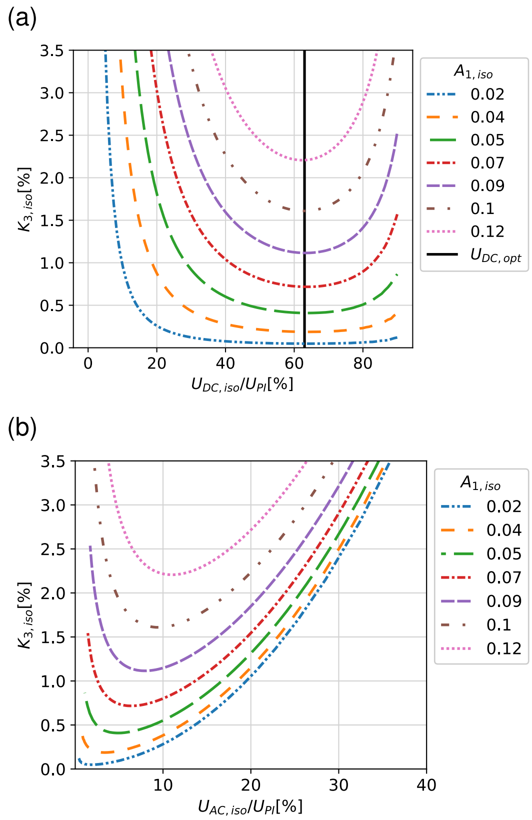

Fig. 5 K_3 in % by a numerical evaluation of equation (2) for iso-A_1 working points for a variation of the bias voltage (a) and the signal voltage (b)

Conclusion

Previously, a distortion analysis of the third harmonic distortions for constant signal-to-bias-ratios under a variation of the bias voltage was utilized for a non-destructive pull-in estimation. Here, this approach is extended to not only reproduce the distortions but also the sound pressure signal of the push-pull NED microspeaker. The reduced-order model forms a solid base for investigations of different working points once the parameter estimation is available. Different combinations of signal and bias voltages can lead to the same fundamental response for a differential drive, but they differ with respect to their fidelity. Choosing the bias voltage as 63% of the pull-in voltage can reduce the third harmonic distortion, the main remaining source of total harmonic distortions.

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