

A Mixed-Level Model for Force-Feedback Controlled Piezoelectric MEMS Microphones

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Summary:

We present a mixed-level model for a force-feedback controlled piezoelectric MEMS microphone. The approach combines a 2D axisymmetric FEM model of the piezoelectric transducer with an equivalent circuit describing parasitic electrical effects. The model enables accurate prediction of electromechanical behavior and electrical feedthrough over a wide frequency range up to 100 MHz. The implementation supports co-simulation with force-feedback controller models via LiveLink™ to Simulink.

Keywords: piezoelectric MEMS, MEMS microphones, force-feedback control, mixed-level modeling

Introduction

Advanced system-level modeling is essential for the design of force-feedback controlled MEMS sensors, as it enables performance optimization and controller co-design [1]. In piezoelectric MEMS microphones (PMICs), force-feedback control (FFC) improves linearity, increases resonance frequency, and raises the acoustic overload point [1,2]. This work presents a mixed-level model of a recently introduced PMIC design featuring a fully clamped corrugated single-layer membrane [3,4]. The pseudo-bimorphic architecture enables single-ended signal readout and force-feedback actuation. Previous studies identified electrical feedthrough (FT) as a key limitation for controllability [5]. While an equivalent circuit model addressing FT was introduced in [6], a complete system description requires coupling detailed membrane mechanics with circuit-level parasitics. We therefore combine a FEM-based mechanical and piezoelectric model with a lumped circuit model and implement the system in COMSOL Multiphysics. Using LiveLink™, the model supports co-simulation with controllers designed in Simulink. The functional principle and control scheme are shown in Fig. 1.

Device Description

Under acoustic excitation, membrane deflection induces compressive stress in corrugation peaks and tensile stress in valleys, resulting in a net charge sensed by electrodes placed as shown in Fig. 1 (sensing mode). Electrical actuation is achieved by applying a voltage V_{act} between peak and bottom electrodes, exploiting the inverse piezoelectric effect.

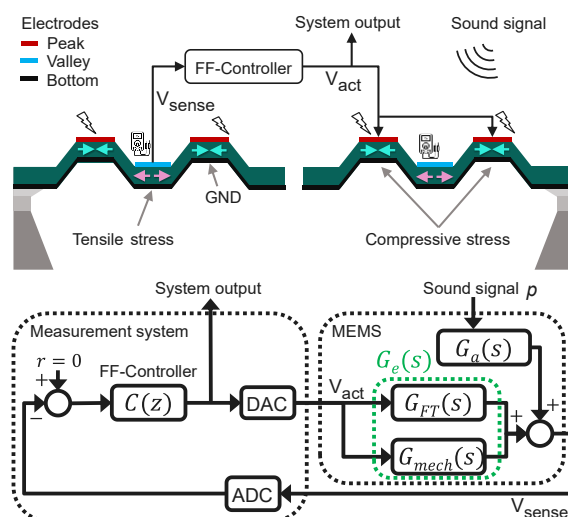


Fig. 1. Functional principle and control scheme of a force-feedback controlled piezoelectric microphone.

In force-feedback operation, the sensed voltage V_{sense} at the valley electrode is fed into a digital controller $C(z)$, whose output V_{act} counteracts membrane motion and minimizes V_{sense} . The effective sensor signal is therefore V_{act} . However, electrical feedthrough causes a direct coupling between actuation and sense electrodes, independent of mechanical deformation. Fig. 1 illustrates the corresponding control and measurement scheme. The transfer functions $G_{mech}(s)$ and $G_{FT}(s)$ describe the mechanical and electrical contributions to the electrical frequency response $G_e(s)$, while $G_a(s)$ models the acoustic path. The controller is implemented on an FPGA-based measurement system.

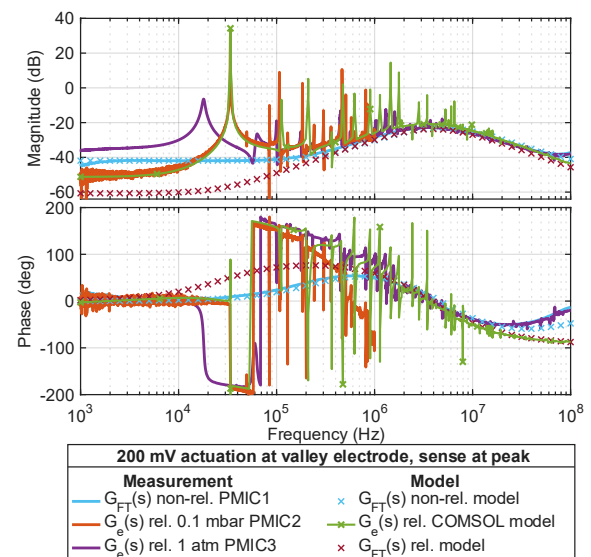


Fig. 3 compares measured and simulated electrical transfer functions for different samples. Released samples show reduced parasitic capacitances to the conductive Si-substrate and between actuation and sense contacts. PMIC2 is bonded to an ASIC amplifier, enabling vacuum measurements but limiting the bandwidth to 1 MHz. To extend the frequency range to 100 MHz, PMIC3 is measured at atmospheric pressure without an ASIC. The mixed-level model accurately reproduces $G_e(s)$ of PMIC2 up to 1 MHz and closely follows the response of PMIC3 at higher frequencies, demonstrating its validity over the full measurement range. Due to the 2D axisymmetric formulation, only radially symmetric modes are captured. Angular resonances are therefore not represented.

The presented mixed-level model shows good agreement with experimental data and enables co-simulation of complex MEMS behavior with force-feedback controllers. Future work focuses on extending the model with a transmission-line formulation to include thermoviscous effects of the sound port inside the PCB.

- [1] doi: 10.1002/9783527647132.ch16
- [2] doi: 10.5162/sensorsen2024/C3.2
- [3] G. Bosetti, A Novel High-SNR Full Bandwidth Piezoelectric MEMS Microphone Based on a Fully Clamped Aluminum Nitride Corrugated Membrane. In: *2023 22nd International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)*, 366–369; 2023.
- [4] doi: 10.1109/EuroSimE60745.2024.10491462
- [5] doi: 10.30420/456614127
- [6] doi: 10.1109/SENSOR59705.2025.11330565

The mixed-level model combines a 2D axisymmetric FEM model including solid mechanics, electrostatics, and the piezoelectric effect with a lumped circuit model representing parasitic circuitry of the real device. The equivalent circuit parameters were identified from LCR measurements on multiple samples (see Fig. 2 (a)). Measured admittance data are converted into the corresponding voltage response using (1).

Capacitance values are additionally extracted from FEM simulations and analytical parallel-plate approximations of the material stack. The electrical feedthrough $G_{\text{FT}}(s)$ is obtained from a non-released membrane (PMIC1). Remaining parameters are obtained by fitting the model to the measured frequency response.