DOI: 10.61782/fa.2025.0034

FORUM ACUSTICUM EURONOISE 2025

A SIMULATION FRAMEWORK FOR PIEZOELECTRIC MEMS SPEAKERS: MODELING, INTEGRATION, AND VALIDATION

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ABSTRACT

We present a simulation framework for piezoelectric, cantilever based Micro-Electro-Mechanical-Systems (MEMS) Speakers. Contrary to electrodynamic speakers, those speakers present a capacitive electrical load, necessitating a modified modeling approach.

Using measurements from a Laser-Doppler-Vibrometer (LDV) we determine a set of parameters derived from the well known Thiele-Small-Parameters (TSP) using the Known Mass Method.

The acoustic load on the back of the membrane is strongly influenced by the cavity structure within the speaker. We use Finite-Element-Analysis (FEA) to calculate the acoustic impedance acting on the membrane back side. A lumped element representation of this impedance is included in the full model.

We present the integration of a MEMS speaker into an earphone design using a simulation driven approach based on the previously described model.

The acoustic effects of the enclosure, as well as the artificial ear are simulated using the finite element method. The results are validated against acoustic measurements of a 3D printed version of the earphone. We show that the models can accurately predict the frequency response of the MEMS speakers, also under complex acoustic load conditions.

Keywords: *MEMS Speakers, Transducer Simulation, Microspeakers*

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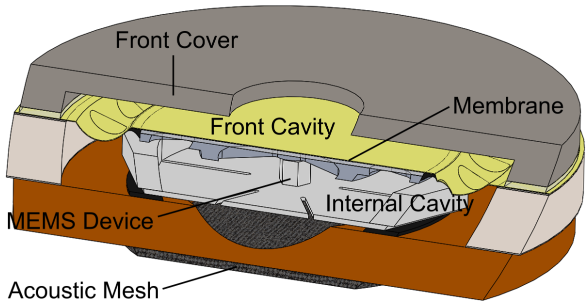

Figure 1. A drawing of the MEMS speaker's internal structure. (Diagonal Cross Cut). The overall diameter of the speaker is 5 mm

1. INTRODUCTION

1.1 Piezoelectric MEMS Speakers

Cantilever based piezoelectric Micro-Electro-Mechanical-Systems (MEMS) Speakers are transducer elements utilizing the force provided by the inverse piezoelectric effect to actuate a moving surface, leading to the radiation of sound. There are two distinct approaches. While some designs use the surface of the piezoelectric MEMS device itself [1], our work concerns itself with designs that utilize an additional membrane component that is connected mechanically to the piezoelectric cantilever element.

Figure 1 shows a cross cut through such a MEMS speaker. The acoustically active area (membrane) is shown in yellow. The MEMS device is shown in light gray. The two elements are mechanically connected to each other.

The MEMS device is the active motor unit of the

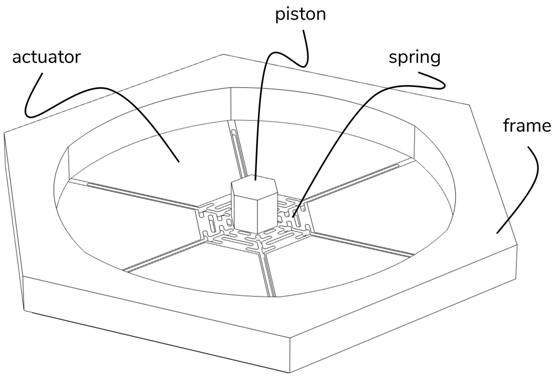

Figure 2. Architecture of the MEMS device

speaker. It consists of four main structural building blocks. (Figure 2)

The frame supports the MEMS device and provides mechanical and electrical connection towards the base of the speaker assembly.

The actuators are piezoelectric cantilevers that provide the driving force. The composite layer stack of the actuators consists of the electrodes, the active piezoelectric layer and the passive structural layer. Due to the inverse piezoelectric effect, applying a voltage at the electrodes across the active layer leads to a deformation, this results in a bending motion of the cantilever. Moving the central region of the device upward and downward where the piston and springs couple the movement to the membrane element of the speaker.

The active piezoelectric layer is made from Lead zirconate titanate (PZT), specifically, epitaxial PZT with highly ordered crystal structure, providing self-poling and high linearity. [2] The passive structural layer is a polymeric film. It provides a large elastic reserve for the structure, which is especially crucial for the device to withstand not only normal operation but also extreme events such as drops while handling.

Generally, there are many similarities between this type of piezoelectric MEMS speakers and "traditional" electrodynamic (micro-)speakers. While the motor principle is fundamentally different, both rely on a moving membrane, the movement of which can be described by a single degree-of-freedom oscillator. This is why a slightly modified version of the Thiele-Small Model [3,4] can also be used for piezoelectric MEMS speakers.

The difference is in the transformation between the electrical domain and the mechanical domain. While the force output of an electromagnetic motor is proportional to the current flow through the voice coil, the force output from a piezoelectric element is proportional to voltage. [5]

1.2 TSP Measurement

Traditional parameter measurement involves adding a known mass or enclosing the speaker in a small, known, volume, both altering the resonance frequency. The change in resonance frequency is then used to conclude the values of the TSP [6]. Since resonance appears as a clearly visible peak in electrical impedance, commercial systems typically use impedance measurements for both methods.

However, the usage of this approach is limited for piezoelectric MEMS speakers due to two factors. First, their impedance is predominantly capacitive. Figure 3 shows the difference to the impedance of an electrodynamic (ED) speaker. Common algorithms are designed for ED speaker impedance profiles. Making them incompatible with the capacitive impedance of piezoelectric MEMS devices.

Secondly, the very small internal dimensions of piezoelectric MEMS speakers (as shown in Figure 1) have a significant influence on the acoustic speaker performance. These internal cavities act as acoustic impedance, influencing all moving surfaces within the speaker, and therefore the speaker's movement.

1.3 Ear Simulators

Ear simulators, or couplers, play a crucial role in the accurate and standardized assessment of auditory devices by mimicking the acoustic impedance of the human ear. The IEC 60318 series defines various coupler types, among which the occluded ear simulator specified in IEC 60318-4 is the most widely used in earphone design. However, its specification is limited to the 100 Hz to 10 kHz frequency range.

The RA0403 (GRAS Sound Vibration A/S, Holte, Denmark) is compatible with the IEC 60318-4 standard but includes design modifications that extend its operational frequency range up to 50 kHz. [7]

2. METHODS

2.1 Model Structure

The piezoelectric MEMS speaker is modeled as a damped mass spring resonator with one degree of freedom. This corresponds to the membrane moving as a piston. All

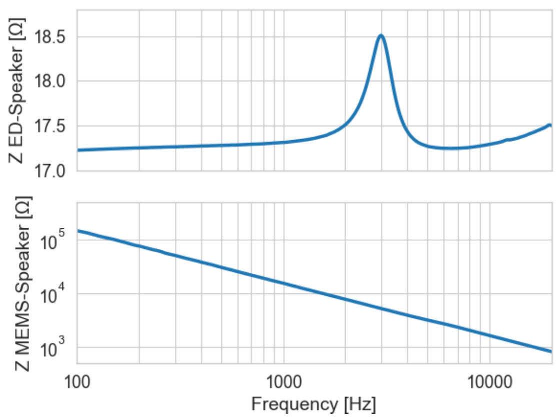

Figure 3. Comparison between the typical impedance curve of a electrodynamic (ED) speaker (RB-E06016F-007R) and a piezoelectric MEMS speaker (USound UA-C0503-3T)

higher order modes, like membrane deformation, are not considered.

The response of a dampened mass-spring resonator is given by the equation of motion. (1)

$$F_p = M_{ms}\frac{d^2x}{dt^2} + R_{ms}\frac{dx}{dt} + K_{ms}x \tag{1}$$

Expressing the frequency response

$$\begin{aligned} x = A&\frac{1-T^2}{(1-T^2)^2+(2\zeta T)^2} \\ +jA&\frac{2\zeta T}{(1-T^2)^2+(2\zeta T)^2} \end{aligned} \tag{2}$$

where A is the deflection per voltage, T is the tuning and ζ is the damping ratio.

$$T = \frac{2f\pi}{\omega_0} \tag{3}$$

$$\omega_0 = \sqrt{\frac{K_{ms}}{M_{ms}}} \tag{4}$$

$$\zeta = \frac{R_{ms}}{2\sqrt{K_{ms}M_{ms}}} \tag{5}$$

$$a = x \cdot (2j\pi f)^2 \tag{6}$$

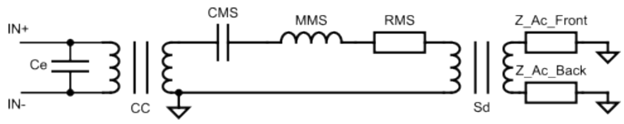

Figure 4. The basic equivalent circuit used to describe the MEMS speaker. $C_{MS} = {}^1/_{K_{MS}}$

The model is represented using and lumped parameters with the equivalent circuit shown in Figure 4. We use the Force-Voltage (FU) analogy for the mechanical domain. As the force provided by the MEMS device is directly proportional to the voltage applied, the effort variable voltage in the electrical domain is directly transformed into the effort variable force in the mechanical domain.

To model this relation a parameter referred to as the Coupling Constant (CC) is introduced. It replaces the Force Factor (B_L) typically used in loudspeaker models. The Coupling Constant is given in N/V.

$$A = \frac{CC}{K_{ms}} \tag{7}$$

Allowing the use of a ideal transformer to interface the two domains in the equivalent circuit. The mechanical spring stiffness K_{ms} is represented by its inverse, the compliance C_{ms}

The full model and any Finite-Element-Analysis (FEA) is set up and solved in COMSOL Multiphysics 6.3 (COMSOL Inc. Stockholm, Sweden). We use the lumped electrical circuit physics interface to model the mechanical and electrical domains of the lumped representation. Acoustical simulations are done using FEA.

As with the majority of other transducer principles, the piezoelectric MEMS speaker in question (USound UA-C0504-3T) features an active area (membrane) that is moved to create acoustic pressure. The membrane separates the acoustic front from the acoustic back. An acoustic impedance acts on both sides. The impedance on the front (Z_Ac_Front) is dominated by the ear simulator and the earphone. But, the acoustic impedance on the back (Z_Ac_Back) mainly arises in the small air cavities within the speaker. (Assuming a reasonably open ventilation towards the back)

We calculate Z_Ac_Back using FEA. A 3D representation of the cavity within the speaker is created based on technical drawings. 1/6 of the speaker is used for the simulation as it is rotationally symmetric and this makes the model computationally less expensive. Due to the small structure sizes found inside the speaker, the calculations are done in the "Thermoviscous Acoustics, Frequency Domain Interface" of the COMSOL Acoustics Module. This interface calculates the viscous and thermal losses occurring in close vicinity to the boundaries. [8]

The external back volume of the speaker is assumed to be infinitely big. In this model, the membrane is moved with a constant velocity for each frequency point. This allows the calculation of the acoustical impedance by evaluating the acoustic pressure on the membrane surface.

$$Z = \frac{p}{q} \tag{8}$$

Where p is the average acoustic pressure at the active area ("membrane") and q is the volume flow rate. This is equal to the integral of the mechanical velocity over the active area. The calculated impedance is a complex valued function of frequency. Discrete frequency points are exported.

The frequency points are then included for "Z_Ac_Back" as seen in Figure 4. As described before, this circuit is implemented in the COMSOL model. "Z_Ac_Back" is integrated as a "User Defined" impedance in the Lumped Speaker Boundary Condition. "Z_Ac_Front" however is dependent on the acoustical load from the ear(-simulator) and the coupler adapter/earphone.

2.2 Added Mass Method

The TSP are typically measured in free air, where results are affected by acoustic impedance. To eliminate these external acoustic influences and accurately determine the intrinsic mechanical parameters of the speaker assembly, measurements were carried out in a vacuum using a Laser-Doppler-Vibrometer (LDV) (PSV 500, Polytec GmbH, Waldbronn, Germany). The vacuum environment effectively isolates the system from acoustic loading, allowing for the characterization of its purely mechanical behavior.

Equation 1 to 6 describe the frequency response function of a dampened mass spring resonator. The least_squares function of Scipy v1.15.2 is used to determine a set of parameters that satisfactorily describe the loaded and unloaded cases.

2.2.1 *Known Mass*

We cut circular pieces of adhesive copper tape. The pieces used had a mass of 2.5 mg each. The front cover was removed from the speakers to reveal the whole membrane. The speakers were then measured under vacuum ($< 8.7 \cdot 10^{-2} hPa$), so as to remove effectively all influences from the air load (unloaded case). The copper pieces were attached, as shown in Figure 6, and the measurements were repeated within the same conditions (loaded case).

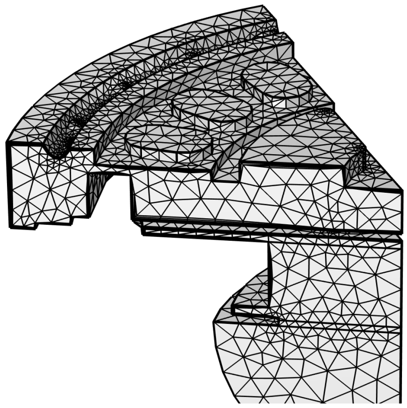

Figure 5. Mesh used to calculate the acoustic impedance of the volume within the speaker packaging

2.3 Acoustic Validation

The predictive quality of the model is validated acoustically by comparing the output to measurements of two scenarios. We use a 1.8 mm long coupler adapter with a diameter of 3 mm to connect the speakers acoustic output to the coupler input. The coupler is used without the conical earmould adapter.

Also, the speaker model is compared to the speaker performance within an earphone prototype. The earphone in question is shown in Figure 7. The piezoelectric MEMS speaker is used as a tweeter. Hence, the design features space for the integration of a ring-shaped electrodynamic woofer, which is outside the scope of this paper. A detailed description of the earphone is provided in [9].

We use a RA0403 (GRAS Sound & Vibration A/S, Holte, Denmark) "High-Resolution" ear simulator to do all reference measurements. The ear simulator is represented in the model by a slightly modified version of the "generic_711_coupler" available in the COMSOL appli-

Figure 6. A circular piece of copper tape is attached to the speaker membrane. Increasing the moving mass by 2.5 mg

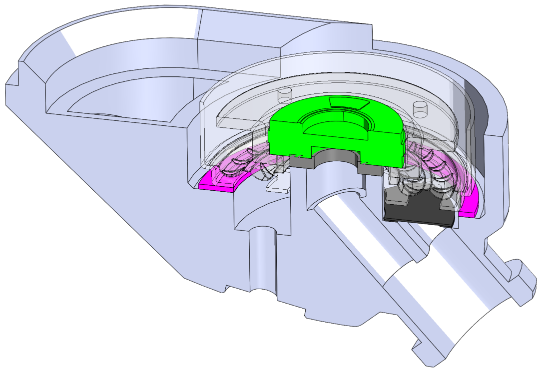

Figure 7. Cross cut of the earphone Design used for model validation. The piezoelectric MEMS speaker is shown in green. The woofer is shown in transparent gray. The silicone rubber eartip is not shown.

cation library. An acoustic impedance of $9000^{Pas}/_{m^2}$ is added to the central, tube shaped, volume of the coupler. Figure 8 shows the alignment of this model and the calibration data provided by the manufacturer.

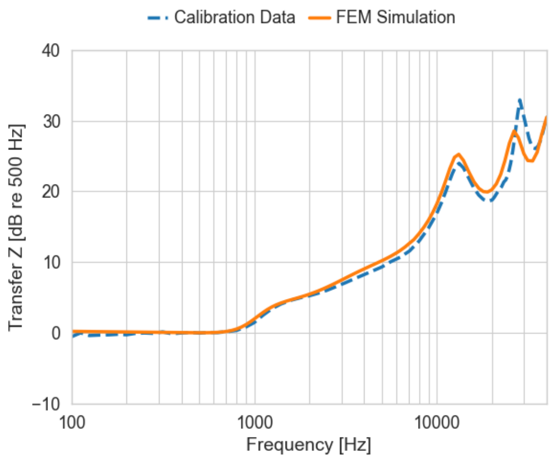

Figure 8. Relative transfer impedance of the used FEM Model of the G.R.A.S RA0403 ”Hi-Res” Ear Simulator and the corresponding calibration data provided by the manufacturer

3. RESULTS

3.1 TSP Measurement

The TSP are calculated with a least squares fit of Equation 2, to both the loaded and unloaded cases. Figure 9 shows the alignment of the fit to the acceleration measured using LDV.

From fitting Equation 6 to the measurement data we can extract the modified TSP, resulting in the values shown in Table 1.

Table 1. The calculated modified TSP

Parameter	Value
M_{ms}	$1.57mg$
K_{ms}	$1.86 \cdot 10^3 {}^{N}/_{m}$
R_{ms}	$4.2 \cdot 10^{-3} {}^{Ns}/_{m}$
CC	$818 \cdot 10^{-6} {}^{N}/_{V}$

3.2 Acoustic Measurements

The simulation model is compared with the acoustical test results gathered in a G.R.A.S RA0403/04 ”Hi-Res” Ear Simulator. The comparative plot is shown in Figure 10. The deviation up to 20 kHz is below $\pm 1\,dB$.

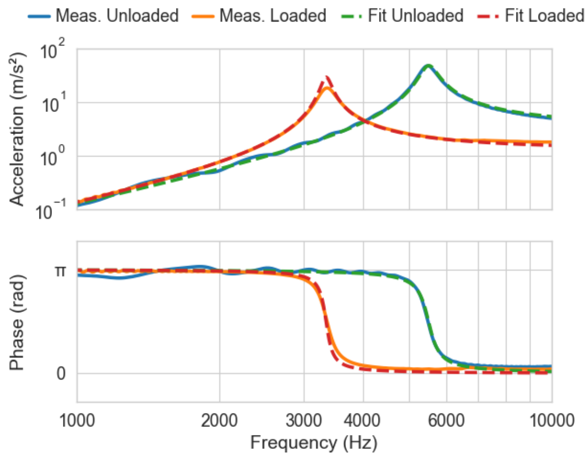

Figure 9. Result of the least squares fit in comparison with the LDV measurement results. The loaded case has a lower resonance frequency.

Above the audible range, the deviation increases continuously. Showing the limit of the single degree-of-freedom approach.

In addition, speakers are evaluated in an application-focused way using a previously developed earphone design. The predictive performance of the model is shown in Figure 11. Within the audible range, the deviation is below $\pm 1.5\,dB$. The position of the resonances is accurate to $\pm 300\,Hz$

4. DISCUSSION

The simulation framework presented addresses the unique characteristics of piezoelectric Micro-Electro-Mechanical-Systems (MEMS) speakers, particularly their capacitive electrical load, which requires a modified modeling approach compared to traditional electrodynamic speakers. We show the adaption of the Thiele-Small-Parameters (TSP) for these speakers and present a way to measure them using Laser-Doppler-Vibrometer (LDV) measurements under vacuum with the Known Mass Method, effectively eliminating the influence of acoustic impedance. The calculated TSP values appropriately describe the speakers mechanical behavior in the audible frequency range.

The integration of the MEMS speaker model into an earphone design was achieved using a simulation-driven

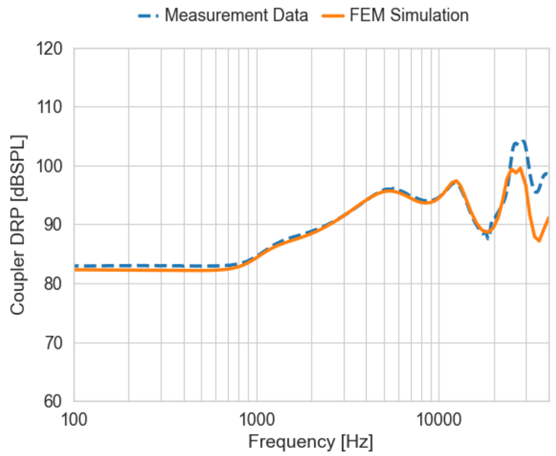

Figure 10. Comparison between the simulation result and the measured performance of the piezoelectric MEMS speaker in the G.R.A.S RA0403/04 "Hi-Res" Ear Simulator. With two different adapter systems

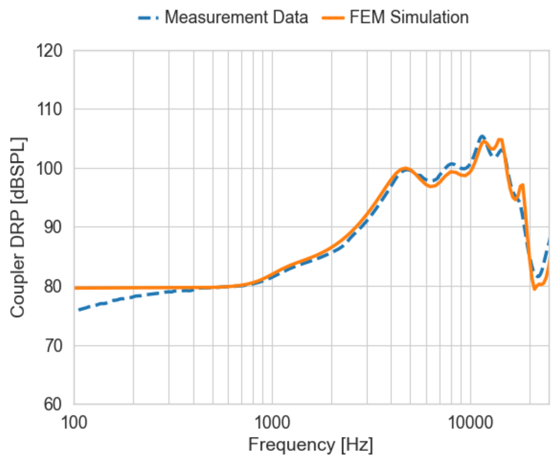

Figure 11. Comparison between the simulation result and the measured performance of the MEMS speaker in the earphone design.

approach incorporating Finite-Element-Analysis (FEA) to model enclosure and artificial ear acoustics. The significant influence of internal acoustic impedance, calculated via FEA of the speaker's cavities, was included in the model.

Acoustic validation demonstrated good agreement between simulation and measurements using a GRAS RA0403/04 "Hi-Res" Ear Simulator and an earphone prototype. Deviations were generally below ±1 dB up to 20 kHz for the ear simulator and below ±1.5 dB within the audible range for the earphone, with accurate resonance prediction. The increased deviation at frequencies above the audible range shows a limitation of the single degree-of-freedom model.

In conclusion, this simulation framework provides a valuable tool for the design and optimization of piezoelectric MEMS speakers and their integration into audio devices by accurately predicting frequency response under various acoustic loads while considering their unique electrical and acoustic characteristics.

Future work could focus on more complex mechanical models. A promising approach would be to go towards lumped representation of a multi degree of freedom model. We would expect this to improve the high-frequency accuracy.

5. ACKNOWLEDGMENTS

We would like to thank our colleagues at USound GmbH for all their previous contributions that went into this paper. Although they are too many to mention individually, we would like to especially thank Paul Heyes for his help with the Laser-Doppler-Vibrometer measurements and Jascha Blinzer for providing the cross sectional view from Figure 1.

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