Multiphysics Modeling of Piezoelectric MEMS Loudspeakers

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Problem and Motivation

MEMS micro-speakers represent an increasingly hot research topic for the last years, as they have the potential to solve some problems currently present in traditional micro-speakers. They promise **higher energy-efficiency** and **cost-efficient mass production** with **tight manufacturing tolerances**. Among the possible different actuating principles, the **piezoelectric** is the most promising. However, the design of effective *all-silicon* piezoelectric MEMS speaker is still an **open problem**:

- at the **design level**, as most current MEMS speakers are not capable of generating a sufficiently high Sound Pressure Level in the whole audible frequency range, with respect to traditional micro-speakers.
- At the **simulation level**, as the computation of Total Harmonic Distortion, which represents a key parameter for accurate reproduction of sound, involves the solution of a complex multiphysics nonlinear system. Only experimental measurements are available so far in the literature.

Objective: SPL and THD simulation

Loudspeakers' main requirements:

- **High** Sound Pressure Level (**SPL**) in the whole audible range (20 Hz-20 kHz)

$SPL = 20log_{10}\left(\frac{p_{rms}}{p_{ref}}\right)$ (dB), with p_{ref}=20 µPa (threshold of human hearing)

- **Low** Total Harmonic Distortion (**THD**)

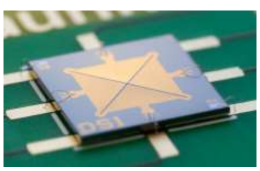
$THD_{\%} = \frac{\sqrt{\sum_{i=2}^{\infty} k_i^2}}{k_1} \cdot 100$, with k_1: RMS pressure amplitude of the fundamental harmonic; k_i: RMS pressure amplitude of higher harmonics

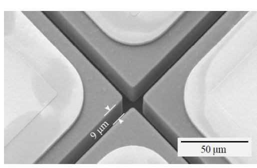
Multiphysics radiation model

Twofold goal of numerical simulations:

- accurate evaluation of the free-field **SPL → full-order linear** simulation in COMSOL Multiphysics, with all involved physics and package effect (i.e. back chamber).
- Identification of the main sources of **THD → nonlinear analysis** with **Reduced Order Modeling (ROM)** through a custom Fortran code.

The speaker geometry taken as reference is the one proposed by the Fraunhofer Institute [1].



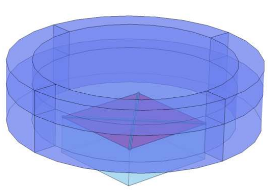


Loudspeaker fabricated by the Fraunhofer Institute.

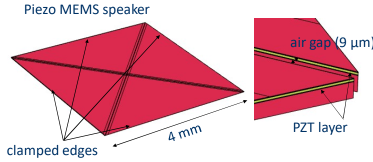
SEM image of the Loudspeaker membrane.

COMSOL modeling: the linear problem

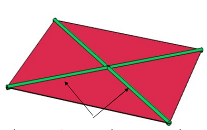
Involved Physics



Electro-mechanics

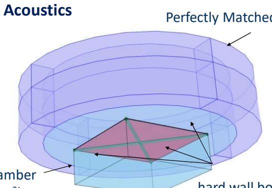


Thermoviscous Acoustics

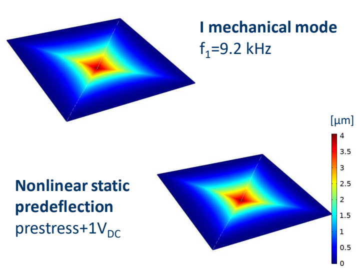


Thermoviscous losses make the four actuators behave acoustically as a single membrane

Pressure Acoustics

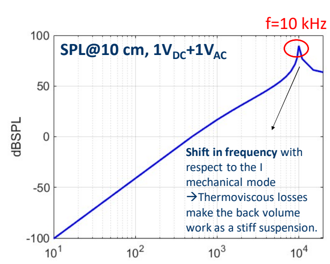


Results



I mechanical mode
f_1=9.2 kHz

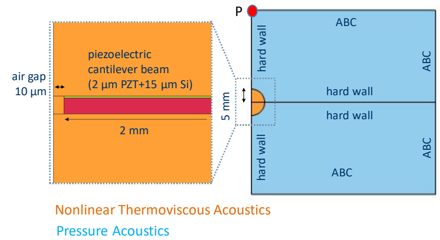
Nonlinear static predeflection
prestress+1V_{DC}



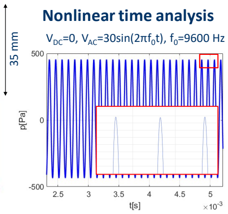
Fortran modeling: the nonlinear problem

Fluid nonlinearities

A 2D simplified model demonstrates that **no distortion in the far-field pressure signal** can be ascribed to convective terms, introduced through a nonlinear thermoviscous acoustics formulation in the air domain near air-gaps.



Nonlinear time analysis



Geometric and material nonlinearities

Mechanics is reduced to a **1dof system** to simulate the speaker behavior due to:
-predeflection due to the Direct-Current (DC) voltage applied on the piezo: V_{DC}
-predeflection due to mechanical prestress induced by the fabrication process
-geometric nonlinearities
-hysteretic behavior of the piezoelectric layer

The model

$\forall \tilde{p} \in C_p$ find $q(t)$ and $p(\mathbf{x},t)$ such that :

$$\ddot{q} + \omega^2(q) = \int_{S_P} pUdS + \sum_{i=1}^{n} P_i^2(V_i)(F_i^p + k^p q)$$

from Implicit Static Condensation [2]; Equivalent nonlinear forcing term [3],[4]

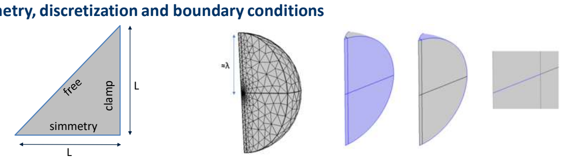
$$\int_{\Omega_A} (\rho\ddot{p}\tilde{p} + k\nabla p \cdot \nabla\tilde{p})d\Omega = \int_{\partial\Omega} k\partial p_n \tilde{p} dS =$$
$$= -\int_{S_{ABC}} \frac{k}{c}\dot{p}\tilde{p}dS - \int_{S_P} \rho k\ddot{u}\tilde{p}dS$$
$$= -\int_{S_{ABC}} \frac{k}{c}\dot{p}\tilde{p}dS - \ddot{q}\int_{S_P} \rho kU\tilde{p}dS$$

$$P^2(t,V) = c_0 + \sum_{i=1}^{n} c_i\cos(2\pi i f t) + s_i\sin(2\pi i f t)$$

Initial predeflection (F_i)
Frequency shift (k_i)

q: modal displacement of the speaker
p :pression variable
U: mass-normalized eigenvector (mechanical mode)
k: air bulk modulus
c: air sound speed
ρ: air density
P: polarization (from experimental hysteresis curves)

Geometry, discretization and boundary conditions



L=2000µm-g/2$\sqrt{2}$ con g=9µm
Out-of-plane thickness:18.33µm

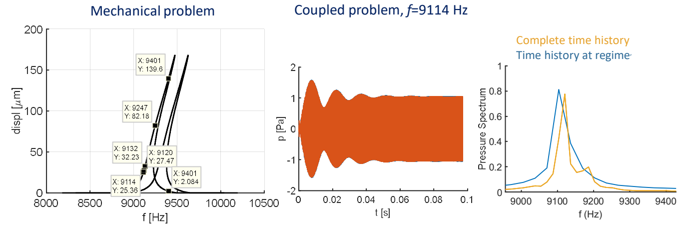
sphere (r=35mm)

hard wall

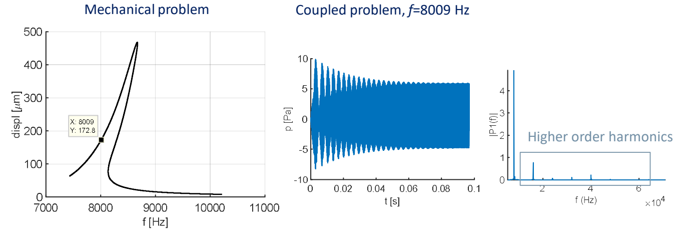
ABC

fluid-structure interaction

Numerical Results: geometric nonlinearities contribution to THD



Numerical Results: geometric + material nonlinearities contribution to THD



Conclusions

Numerical results identify **material nonlinearities** as the **main source of THD.**

[1] F. Stoppel, A. Männchen, F. Niekiel, D. Beer, T. Giese and B. Wagner, "New integrated full-range MEMS speaker for in-ear applications," 2018 IEEE Micro-Electro-Mechanical Systems (MEMS), pp. 1068-1071
[2] A. Frangi, G. Gobat, "Reduced Order Modelling of the non-linear stiffness in MEMS resonators", Int. J. Non-linear Mechanics, vol. 116, pp. 211–218, 2019
[3] A. Frangi et al, "Nonlinear Response of PZT-Actuated Resonant Micromirrors ", J. Microelectromech. Syst. vol. 29, n. 6, pp. 1421-1430, 2021
[4] A. Opreni and A. Frangi, "Full-Order Frequency-Domain Simulations of Nonlinear Piezoelectric MEMS", Nodycon, 2021

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