Comprehensive Harmonic-Domain Simulation of a Thermally-Driven MEMS Accelerometer with Full Noise Characterization

Jacek Nazdrowicz[1], Michał Szermer[2], Maja Tuszynska[3]
[1,2] Lodz University of Technology, Lodz, Poland
[3] Cracow University of Technology, Cracow, Poland
jacek.nazdrowicz@p.lodz.pl

Extended Abstract

High-performance MEMS accelerometers employed in precision sensing applications are increasingly limited by noise, thermal drift, and cross-domain coupling effects that cannot be reliably predicted using simplified or domain-isolated models. Mechanical dynamics, capacitive transduction, temperature-dependent material properties, and electronic readout noise interact in a nonlinear manner, directly influencing noise density, signal-to-noise ratio, and long-term stability. Accurate, full-chain modeling is therefore essential for realistic performance prediction.

This work presents a comprehensive thermoelectromechanical simulation framework for capacitive MEMS accelerometers operating in the harmonic domain. The model integrates nonlinear mechanical dynamics of the proof mass with temperature-dependent stiffness and damping, gap-dependent capacitive transduction including dielectric permittivity drift, a temperature-aware electronic readout chain, and a physically motivated multisource noise synthesis module. Mechanical (Brownian), capacitive, and electronic noise sources are explicitly modeled and propagated through the complete sensing chain within a unified timedomain simulation environment.

The framework supports extensive diagnostic analysis, including time-domain waveforms, FFT spectra, power spectral density (PSD), frequency-dependent signal-to-noise ratio (SNR), noise-equivalent acceleration (NEA), statistical noise distributions, and temperature-induced bias drift. Harmonic excitation at 50 Hz is used to evaluate linearity, bandwidth, and noise behavior under realistic operating conditions. Temperature variation in the range 25–45 °C directly affects mechanical, dielectric, and electronic parameters, enabling realistic assessment of thermal sensitivity.

Quantitative validation is performed against the commercial low-noise capacitive MEMS accelerometer ADXL355. The simulated broadband noise density reaches $22.6\ \mu g/\sqrt{Hz}$, closely matching the nominal device specification. The model reproduces realistic SNR behavior, achieving a peak SNR of 47.7 dB under harmonic excitation. The frequency-resolved NEA exhibits the characteristic three-region structure observed in modern capacitive accelerometers: elevated low-frequency noise dominated by thermomechanical effects, a flat midband plateau governed by white electronic noise, and high-frequency degradation caused by bandwidth limitations.

Fig. 1 presents the acceleration-domain power spectral density obtained from simulation together with the reference noise floor of the ADXL355. The close agreement in both magnitude and spectral shape confirms that the proposed framework accurately captures the dominant noise mechanisms and their frequency dependence without empirical fitting. Temperature-driven bias drift extracted from the simulated output shows correct magnitude and linearity, consistent with reported behavior of precision capacitive MEMS devices.

These results demonstrate that the proposed framework functions as a high-fidelity digital twin of a modern capacitive MEMS accelerometer. By explicitly combining thermomechanical modeling, multisource noise synthesis, and electronic readout effects, the approach enables realistic noise and thermal analysis, early-stage performance prediction, and evaluation of compensation strategies without physical prototypes.

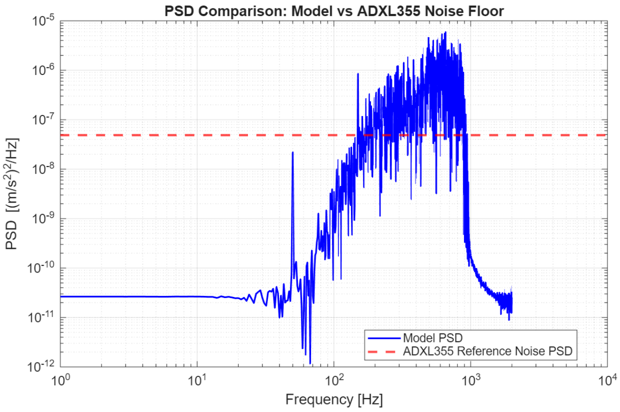

Fig. 1. Acceleration-domain power spectral density (PSD) of the simulated MEMS accelerometer noise compared with the ADXL355 reference noise floor.