

Efficient Prediction of Damping in Acceleration Sensors by Physical Compact Modelling

F. Michael¹, K. Hiller², S. Weidlich², R. Forke³, S. Pregl⁴, G. Schrag¹

¹Technical University of Munich, Munich, Germany

²TU Chemnitz, Chemnitz, Germany

³Fraunhofer Institute for Electronic Nano Systems ENAS, Chemnitz, Germany

⁴Infineon Technologies AG, Dresden, Germany

friederike.michael@tum.de

Summary:

In this work, we use generalized Kirchhoffian networks (GKNs) composed of physically based compact models to efficiently and accurately predict viscous damping in highly perforated moving micromechanical structures. We introduce compact models for slit-shaped perforations, validated by dedicated test structures, and successfully applied them to an acceleration sensor. Comparison with measurements shows good agreement and prove the feasibility of the approach.

Keywords: compact models, transitional flow, damping ratio, MEMS, simulation

Motivation

Damping phenomena in MEMS are difficult to predict, due to complex fluid–structure interaction and gas rarefaction effects present for small dimensions and low-pressure regimes. Accurate simulations based on finite element methods (FEM) are mostly very costly regarding computational efficiency, especially when it comes to coupling of different energy domains. On the other hand, simplified analytical approaches fail to accurately capture those phenomena. Compact model-based methods have proven to bridge this gap by embedding physically based equations into reduced-order formulations that are compatible with system-level simulators. These are designed to solve standard differential equations in a short period of time, which enables fast and reliable simulation of damping behavior in MEMS.

Compact Modelling of Damping by GKNs

We derived a compact modeling approach based on flux-conserving generalized Kirchhoffian networks (GKNs) [1]. GKNs enhance simulation accuracy by resolving details of the structure in a finite network discretization, thus enabling the spatial resolution of e.g. the pressure distribution underneath a movable membrane or contributions of specific parts to the overall noise of the device [2]. The GKN is assembled modularly from a set of compact models. Those are stored in a dedicated library that contains damping models for basic MEMS perforation structures, usually circular or square holes.

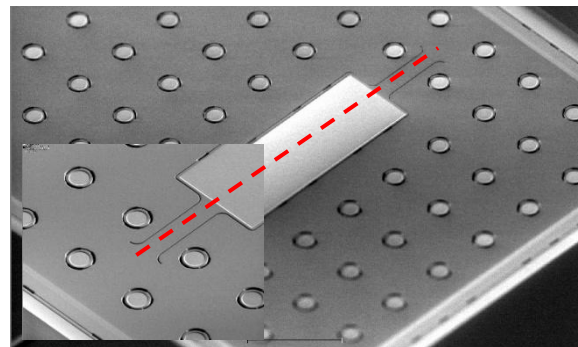


Fig. 1. SEM image of a z-axis accelerometer including a close-up of the perforations. The slits formed in each perforation due to the integrated pillars are clearly visible. The torsion bar is indicated by a red dashed line.

The existing damping models were validated by FEM and measurements for a variety of test structures (cf. sketch in Fig. 2) with different perforation patterns [3]. The models contain correction factors for gas rarefaction and deliver very good results in the range of 1 bar to 1 mbar with an absolute max. error of 10% to 20%.

Compact Model for Slit-shaped Perforations

To cover the impact of regions with high aspect ratio perforations or small slits between the outer edge of the structure and the surrounding material, we derived a new compact model for slit-shaped perforations.

The damping results of the dedicated test structure, whose suspended membrane moves in z-direction like a trampoline generating a piston-like mode shape, displayed in Fig. 2 are in excellent agreement with the simulation from

atmospheric pressure down to the point where the mechanical damping of the device dominates the overall damping behavior at around 2 mbar.

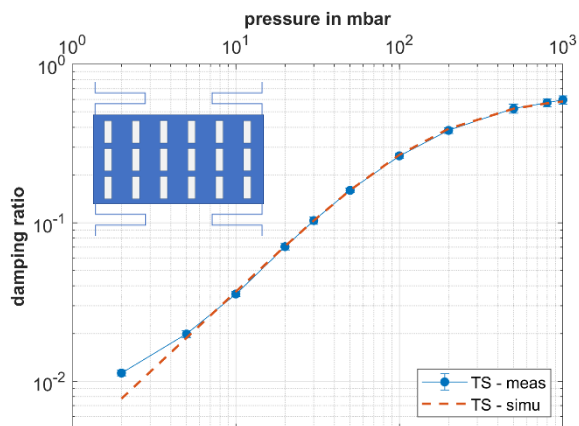


Fig. 2. Damping ratio of test structure with slit-like perforations measured with a laser Doppler vibrometer (LDV) compared with simulation result of respective compact model. A simplified sketch of the test structure is included for explanatory purposes.

Application to Real Sensor

A suitable device to apply the “slit” compact model to is depicted in Fig. 1. The sensor oscillates in z-direction around a torsional spring and has a periodical perforation pattern. Due to the fabrication process each perforation contains a silicon pillar, cf. close-up in Fig. 1. Instead of fully etched holes this creates narrow circular slits for the surrounding gas to flow between the cavity beneath the moving component and the region above it which exerts viscous damping forces. The validated compact model for slit-like perforations is applied to simulate these forces. To preserve the characteristics of the original perforation, the smaller slit dimension and total slit area are kept constant while converting the circular slits into rectangles.

Evaluation of Sensor Results

Fig. 3 shows the measured damping results of the open sensor structure for ambient pressures between 100 mbar and 2 mbar compared with the respective simulation data. Between 20 mbar and 100 mbar the slit model simulation curve is in good agreement with the measured data with an error around 1% - 15% (at the maximum pressure level). At approx. 10 mbar the simulated curve decreases, vastly underestimating the measured damping. One way to explain this behavior is to have a closer look at the Knudsen number (Kn) of the sensor system. Unlike the test structure, which operates at the transitional flow regime for the entire pressure interval, i.e. $Kn < 10$, the sensor enters the molecular flow regime at 10 mbar. At this point the fit parameters used for including gas rarefaction in the compact models are outside their range of

validity. Also, the compact model is based on a rectangular slit geometry not a circular one, which could also impact the simulation especially regarding the incoming fluid flow.

The results clearly display the operational limits of the compact models while simultaneously proving their performance within their respective boundaries. Nevertheless, it remains vital make adjustments for higher Knudsen numbers to expand the compact model simulation into the molecular flow regime.

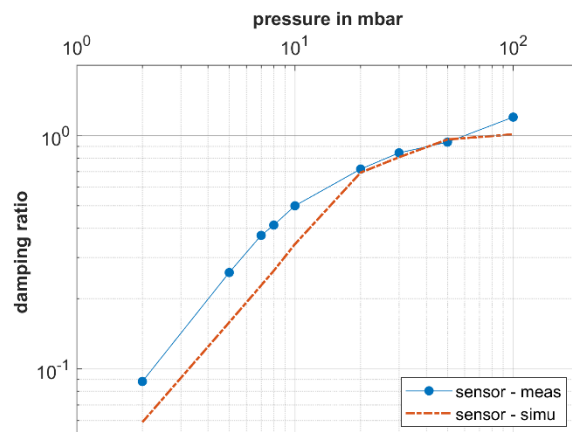


Fig. 3. Damping ratio derived from measurement and simulation of depicted sensor structure for varying surrounding pressures.

Conclusion

We have shown that our approach of implementing compact models in a GKN is highly suitable to give a valid approximation of fluidic damping in the transitional flow regime for standard MEMS devices such as accelerometers. Future investigations will expand into more complex sensor designs. Additionally further research will be done to increase the area of validity of our models into higher Knudsen number areas.

Overall, it becomes clear that by preserving full multi-domain energy coupling, our approach captures the interaction between mechanical motion, fluidic damping, and electrical transduction without sacrificing simulation speed.

References

- [1] G. Schrag, G. Wachutka, „System-Level Modeling of MEMS Using Generalized Kirchhoffian Networks – Basic Principles,” doi:10.1002/9783527647132.ch2.
- [2] M. Niessner, G. Schrag, „Mixed-Level Approach for the Modeling of Distributed Effects in Microsystems,” doi:10.1002/9783527647132.ch7.
- [3] F. Michael, B. Leikam, G. Schrag, „Reliable Damping Simulation of Highly Perforated Micro-Electro-Mechanical Systems through Physical Compact Modeling,” doi:10.3390/proceedings2024097176