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Simulation of Damping Effects in Irregularly Perforated MEMS Devices by Physical Compact Modeling

Friederike Michael, Gabriele Schrag,
Technical University of Munich, Chair of Physics of Electrotechnology
Theresienstraße 90, 80333 Munich, Germany
friederike.michael@tum.de

Summary:
Accurate modeling of damping effects in high-end MEMS devices is a major challenge due to low feature sizes and complex device geometries. By applying a finite network approach with specially derived compact models, we are able to simulate structures with varying perforation patterns and account for the impact of the transition regions between differently perforated areas. Simulations of exemplary test structures with different perforation sizes and patterns prove the feasibility of our approach, which perspectively improves the accuracy of damping estimation beyond state of the art.

Keywords: squeeze film damping, transition flow, MEMS, Kirchhoffian networks, damping ratio

Introduction

Squeeze film damping (SQFD) significantly determines the dynamic performance of various microelectromechanical systems (MEMS), such as micro switches or accelerometers. Their moving parts are usually highly perforated due to etching steps during the manufacturing process and, more importantly, to precisely adjust damping to achieve the desired performance. State-of-the art MEMS devices exhibit therefore a complex, laterally large-scale device geometry with varying feature sizes and perforation patterns [1].

However, a reliable and fast way to accurately predict damping in such large-scale microstructures is still an issue, since most modeling approaches consider uniformly perforated plates only (e.g. [2] [3]), which does not apply to complex MEMS designs with multiple perforation patterns. In this respect, it is also vital to pay special attention to regions where different perforation patterns are adjoining, which has a non-negligible impact on the overall damping .Additionally, small feature sizes as well as packaging under low-pressure conditions require the implementation of geometry-dependent corrections, which account for deviations from continuum-flow-based models.

We present an approach enabling fast, but yet physics-based simulation of distributed damping effects in arbitrarily perforated MEMS devices by a compact modeling approach based on generalized Kirchhoffian networks (GKNs) [4] and apply it to representative test structures.

Modeling Approach and Simulation Concept

Fluidic damping strongly depends on the overall device geometry as well as on the size, shape and density of the perforations. To analyze spatially distributed damping effects the structure is discretized into several elements by a mesh, comparable to FEM, but using a flux-conserving finite network consisting of respective elements, which are classified into groups labeled as part of the boundary, of a perforation or of the non-perforated section of the plate, depending on their location.

In order to model the fluidic damping underneath the plate, we use the modified Reynolds equation with correction factors for rarefied gases at higher Knudsen numbers. It is represented by an equivalent network containing a fluidic resistance, a fluidic capacitance and the varying gap height as the source for the gas flow, see Fig. 1. To model fluid flow into, through and out of a single perforation we use three separate models. The fluidic “channel” resistance has the Hagen-Poiseuille equation as underlying model, with adaptions for square perforations. For flow into and out of the perforations the models introduced by [5] are applied. The outflow at the structure’s borders is modeled with an additional fluidic “boundary” resistance based on the equations derived in [5].

The resulting model of the entire structure is represented by a network with the above-described models attached to its nodes, which enables to read out and visualize the pressure at each node as well as the volume flow rate from one node to another. The models are written in Verilog A,

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which allows implementing the GKN model into a standard circuit simulator.

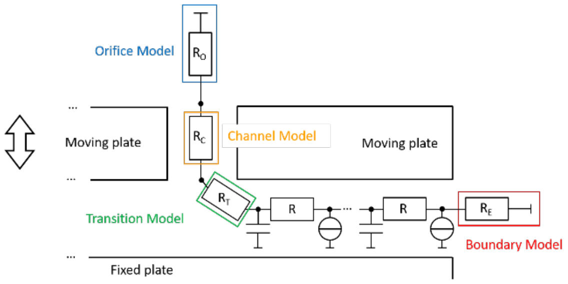

Fig. 1. Cross-sectional schematic of a vertically moving plate with resistances, sources and capacitors modeling fluid flow at the respective nodes.

This offers several advantages regarding the simulation of complex MEMS structures. Aside from the possibility to add custom models, it enables the coupling of damping models to GKN models of other energy domains and electric circuitry. Most importantly, these tools are designed to solve a large number of ordinary differential equations (i.e. our distributed finite network) within a minimum of time, which increases simulation speed significantly.

Simulation Results

The feasibility of the presented simulation concept is demonstrated for test structures with varying perforation patterns, as depicted in Fig. 2b. They consist of a thick perforated plate with two differently sized square perforations arranged in a chessboard-like manner for design convenience and to ease fabrication. However, the approach is also applicable to a design with perforations of varying size and shape, which are randomly scattered over the structure's surface.

The damping ratio is calculated for a pressure range of 1 Pa to 300 kPa. The results are presented in Fig. 2a along with the results of two structures perforated evenly with large and small square-sized perforations, respectively. The pressure-dependent damping ratio for the "chessboard" reveals to be slightly higher than those for the large square holes and lower than those for the small square holes. For pressures lower than 1000 Pa, the difference between the damping ratios remains almost constant. At higher pressure values the damping for the structure with the small holes increases notably when compared to the other two test structures. This shows that impact of the small holes in the "chessboard" is mostly compensated by the large holes, which meets the physically expected result. Newly fabricated test structures are on their way to be characterized via laser Doppler vibrometry in order to validate the simulation. Results will be presented at the conference.

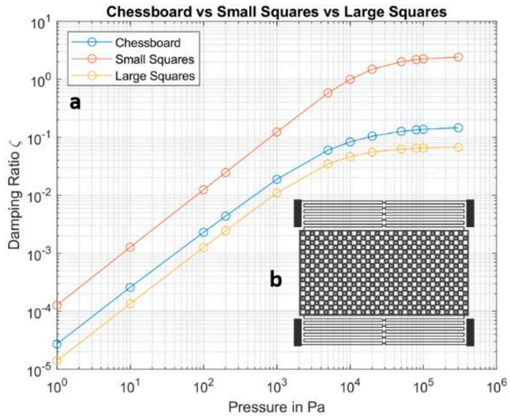

*Fig. 2 **a)** Damping ratio ζ of three differently perforated, exemplary test structures for pressures from 1 Pa to 300 kPa, with large square perforations (yellow), small squares (red) and "chessboard" perforation as depicted in Fig. 2b (blue). **b)** Test structure connected to folded cantilever springs with two differently sized square perforations, assembled in a checkered manner.*

It is noteworthy, that the simulation results for the test structures with around 650 perforations each are obtained within seconds, which shows the efficiency of our approach and the potential to apply it to more complex and large-scale devices as described e.g. in [1].

Outlook

The massive save of simulation time as well as the customization of models to specific requirements opens up new perspectives for accurate damping prediction in microsystems design beyond the current state of the art.

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