Squeeze-Film Damping in Perforated Microstructures: Modeling, Simulation and Pressure-Dependent Experimental Validation

Martin Niessner*, Gabriele Schrag*, Jacopo Iannacci** and Gerhard Wachutka*

*Institute for Physics of Electrotechnology, Munich University of Technology, Arcisstrasse 21, 80290 Munich, Germany, niessner@tep.ei.tum.de
**Fondazione Bruno Kessler (FBK), MEMS Research Unit, Via Sommarive 18, 38123, Povo di Trento, Italy, iannacci@fkb.eu

ABSTRACT

Two compact models and one mixed-level model of squeeze-film damping in perforated microstructures are benchmarked w.r.t. pressure-dependent experimental data of three microstructures of different sizes and with different perforation levels. The mixed-level model shows very good agreement with the measured data. The maximum error at normal pressure is 4 %. The compact models show acceptable agreement for the largest structure, but show errors exceeding 30 % for the smaller structures. An analysis of pressure profiles indicates that the considerable error of the compact models originates from neglecting boundary effects. The mixed-level model includes boundary effects and is thus able to produce accurate results for all of the three structures.

Keywords: MEMS, squeeze-film damping, modeling, experimental validation, benchmark

1 MOTIVATION

The reliable estimation of squeeze-film damping (SQFD) is a prerequisite for the computer-aided design (CAD) of various types of microelectromechanical systems (MEMS). The proper operation of several MEMS accelerometers requires a specific magnitude of damping forces to be present. Thus, the pressure level within the hermetic package corresponding to the desired damping force has to be calculated. The sensitivity of capacitive MEMS microphones can be enhanced if the SQFD acting on the microphone membrane is minimized whilst the area of the perforated detection electrode is kept as large as possible. This kind of optimization requires an accurate and predictive model of SQFD.

However, the modeling and simulation of SQFD is a challenging task since SQFD is, by its nature, a distributed effect that cannot be generally lumped into a compact model. Moreover, due to the small geometrical dimensions and especially at low pressure, gas rarefaction becomes eminent, making the modeling of SQFD on the basis of classical continuum theory a delicate issue.

The compact models presented by Bao et al. [1] and Veijola [2] are based on the Reynolds equation [3] and are widely used by the MEMS community for the calculation of SQFD, even though a systematic experimental validation of these models was not available for several years. Only recently, Veijola et al. [4] and De Pasquale et al. [5] presented first experimental evaluations of the models by Bao and Veijola, but at normal pressure only. Veijola et al. [4] investigated 6 structures and showed that the relative error of the compact model by Bao as well as of his own compact model can be as high as 20 %. De Pasquale et al. [5] investigated 34 devices and showed that the relative error of the compact model by Veijola exceeds 63 % for some of the structures.

These findings prompted us to initiate an experimental study for the evaluation of an alternative SQFD modeling approach, namely the mixed-level model (MLM) as suggested in [6], and to benchmark the MLM versus the compact models by Bao and Veijola.

2 MODELING

In order to ease the later discussion of our experimental results, this section briefly outlines the characteristics of the three different models used in our study.

Bao et al. [1] derived a compact model for SQFD by introducing an additional term into the Reynolds equation that models the vertical flow rate through the perforations. This additional term is integrated together with the other terms of the Reynolds equation across the area of the perforated microstructure. The result is a compact analytical expression. Rarefaction effects are not accounted for.

Veijola [2] derived a compact model for SQFD assuming that a perforated microstructure can be decomposed into an array of perforation cells. A perforation cell is a cell with a hole in its center. Furthermore, Veijola assumes that the air within a perforation cell enters and leaves through the hole of the cell only. Consequently, only the fluidic resistance of one “master cell” has to be computed. A homogenization approach is employed in order to get the overall damping force. Both, physics-based compact models and expressions extracted from FEM simulations are used to calculate the damping force on the master cell. Rarefaction is taken into account by using correction factors that are extracted from fluidic FEM simulations employing slip flow boundary conditions.

Schrag et al. [6] propose a mixed-level approach to model SQFD. A finite network is employed for the spatially distributed evaluation of the Reynolds equation beneath the non-perforated part of the microstructure. At the position of holes, physics-based compact models describing the vertical in- and out-flow of air are added to the respective nodes of the finite network. Similarly, physics-based compact models are added to the nodes of the fluidic network that are located along the outer boundary in order to take finite size effects into account. Generalized Kirchhoffian network theory provides the theoretical framework for the model. Correction factors derived by Veijola are employed in order to account for gas rarefaction [7]. Thus, the mixed-level model (MLM) is, in contrast to the models by Veijola and Bao, not a compact model but a distributed system-level model with a large number of degrees of freedom, but still much less when compared to a FEM model. Moreover, due to the spatially distributed evaluation of the Reynolds equation and the perforations, the MLM is able to take the (modal) deformation of the moving components of the microstructures into account [7] whereas the models by Bao and Veijola allow for rigid body motion only.

3 DEMONSTRATORS AND EXPERIMENTAL SETUP

In our study, we investigated the SQFD on the two electrostatically controlled microresonators (A4 and B4) and the electrostatically controlled RF-MEMS switch (RFS) shown in Fig. 1. Table 1 summarizes the technical data of the structures. The three microstructures have perforation levels between 23 % and 46.9 %, have between 18 and 903 holes, have different thicknesses and, thus, represent a challenging test batch for the modeling and simulation of SQFD.

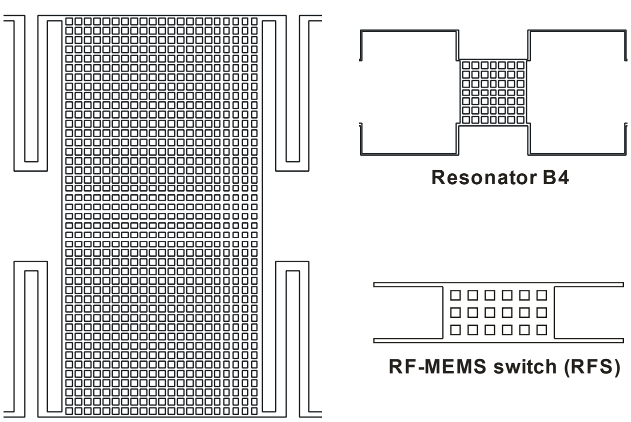

Figure 1: Layout of the two microresonators and the RF-MEMS switch.

		Device		
		A4	**B4**	**RFS**
Material		Silicon	Silicon	Gold
Membrane width	[µm]	425	139	140
length	[µm]	850	133	260
thickness	[µm]	15.65	15.65	5.2
Average gap	[µm]	2.2	2	3.1
Hole side length	[µm]	13.3	13.3	20
Width between holes	[µm]	6.3	5.7	20
Boundary frame width	[µm]	avg. 8.45	avg. 3.5	20
Number of holes		21 x 43	7 x 7	3 x 6
Perforation level	[%]	44.2	46.9	23
Resonance frequency	[kHz]	30	44	14
Q_{EXP} at 960mbar		17.35	37.47	13.58

Table 1: Technical data of the structures shown in Fig. 1. The geometric dimensions were measured using a white-light-interferometer NT1100 DMENS from VEECO. The perforation level is defined as the ratio of the area of all holes and the total area of the perforated membrane.

We chose the quality factor as measure for the quantification of SQFD. The quality factors of the three microdevices were extracted using a laser scanning vibrometer (see Fig. 2). First, the devices were electrostatically excited using a white noise signal. Second, the frequency spectra of the devices were measured. Third, the quality factors were calculated from the spectra using the 3dB-bandwidth method. The vibrometer is equipped with a specifically developed pressure chamber with electronic pressure control that enables the measurement of quality factors at different pressure levels.

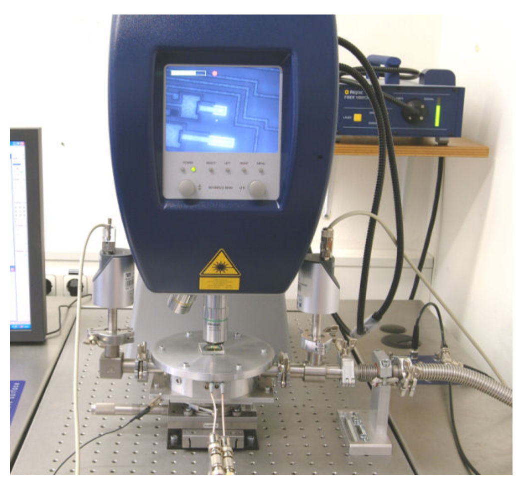

Figure 2: Experimental setup consisting of a POLYTEC MSA-500 and a chamber with electronic pressure control.

4 RESULTS AND DISCUSSION

Fig. 3 shows the quality factors of the three structures versus pressure measured using the setup shown in Fig. 2. The quality factors of all structures are low at normal pressure (see values given in Table 1), increase with falling pressure, but only until a plateau is reached where the quality factors remain at a constant level. This behavior is due to other damping mechanisms like thermoelastic damping [8] and anchor losses [8] that dominate in the low pressure regime and limit the quality factors.

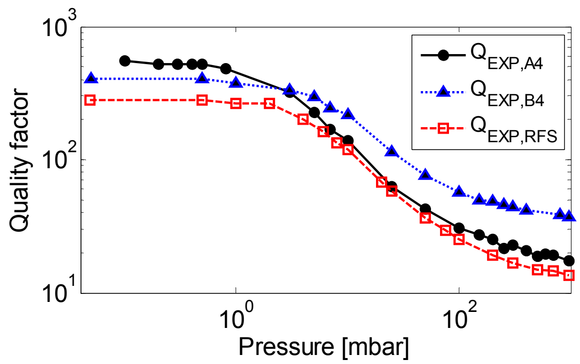

Figure 3: Measured quality factors of the three demonstrators versus pressure.

Fig. 4 compares the experimentally extracted quality factors to the simulated ones using the MLM as presented in [6,7]. The MLM shows very good agreement at normal pressure with a relative error w.r.t. the measurement of less than 4 %. This demonstrates that the MLM, with its finite network for the spatially distributed evaluation of the Reynolds equation and its locally attached compact models, is able to deliver accurate and predictive results for different types of geometries.

With falling pressure, the MLM reproduces the measured behavior with acceptable agreement as long as the plateau is not yet reached. An error threshold of 15 % is exceeded only for pressures lower than 200 mbar. This indicates that the correction factors for rarefaction are presumably reliable for pressures higher than 200 mbar.

The MLM is now benchmarked with the compact models by Bao and Veijola. The benchmark is performed at normal pressure only in order to minimize the influence of the correction factors accounting for rarefaction. Table 2 summarizes the measured and calculated quality factors at normal pressure. The compact models agree best with the measured quality factor of the largest structure (A4) that has the highest number of perforations, but show errors exceeding 30 % for the smaller test structures (B4 and RFS).

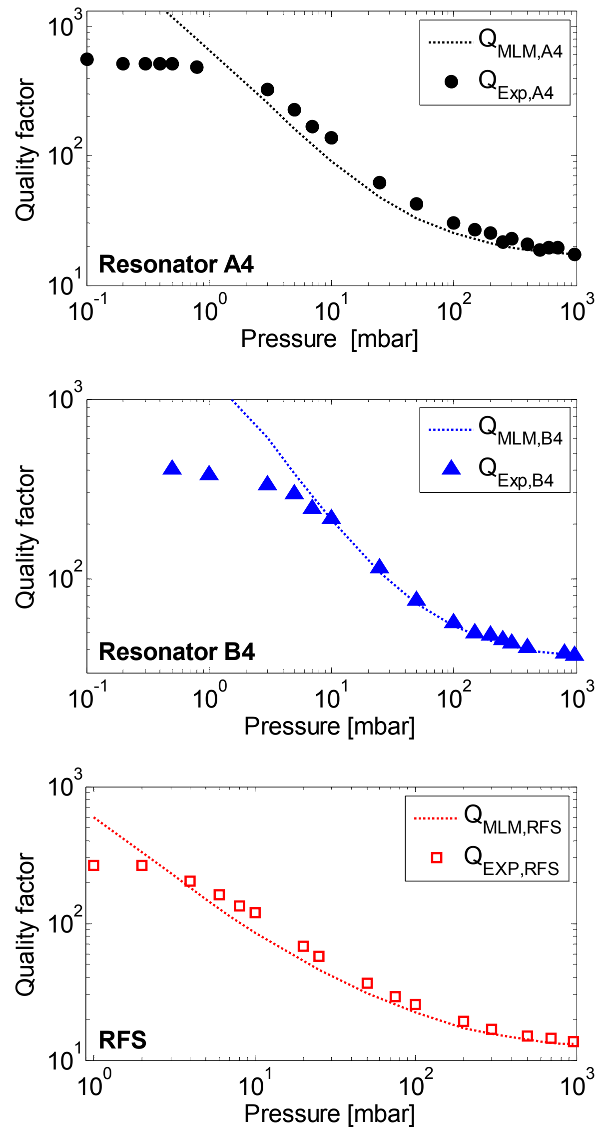

Figure 4: Comparison of the measured and simulated (mixed-level model) quality factors versus pressure.

	A4	B4	RFS
Q_{EXP}	17.35	37.47	13.58
Q_{MLM} [6,7]	17.36 (-0.1 %)	37.39 (+0.2 %)	13.08 (+3.7 %)
Q_{BAO} [1]	16.18 (+6.7 %)	24.96 (+33.4 %)	6.98 (+48.6 %)
$Q_{VEIJOLA}$ [2]	15.25 (+12.1 %)	19.93 (+46.8 %)	18.04 (-32.8 %)

Table 2: Measured and calculated quality factors of the devices at normal pressure, i.e. 960 mbar. The relative error is put in brackets. A negative value indicates an underestimation of the measured quality factor whereas a positive value indicates an overestimation.

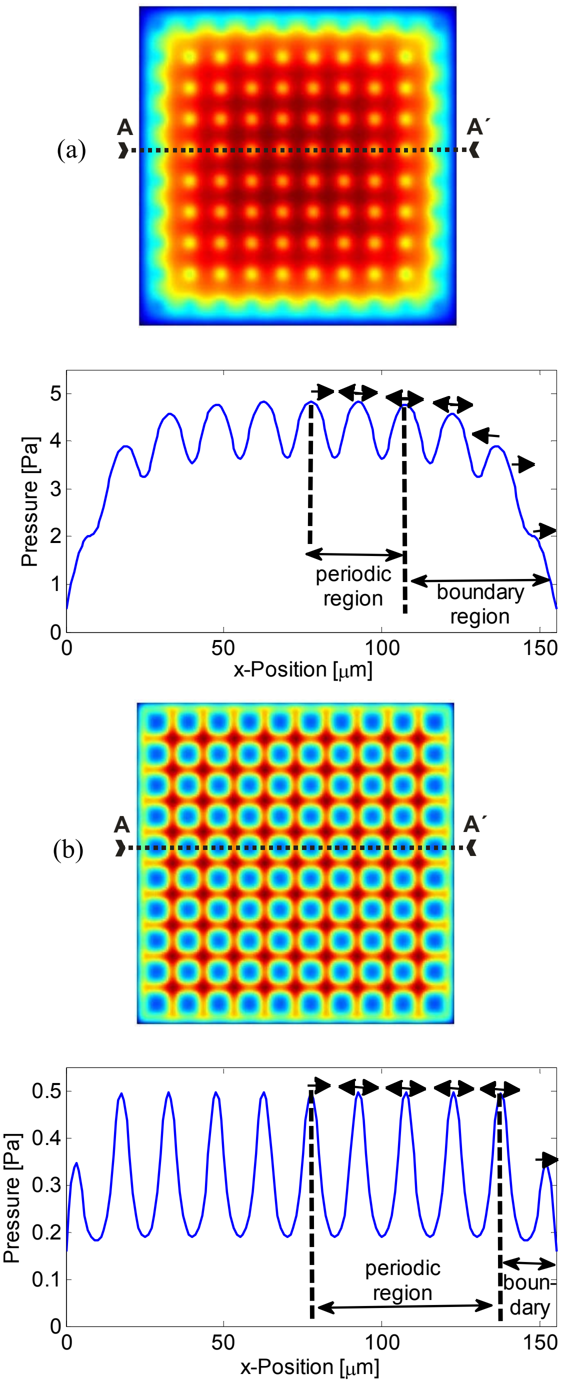

Figure 7: Pressure profiles in the gap of an oscillating quadratic membrane (150 x 150 μm) once with a moderate perforation level (a) and once with a high one (b). The plot beneath each picture shows a cross-sectional cut of the pressure profile in the gap along the dotted lines A--A´.

The reason for this significant deviation can be explained by analyzing Fig. 7. The figure shows the pressure profiles in the gap of a quadratic membrane for a moderate and a high perforation level obtained by FEM simulation. In case of moderate perforation, the pressure profile has a trapezoidal shape consisting of a boundary region where a certain amount of air leaves across the boundary and an inner periodic region where the air leaves entirely through the perforation holes as the boundary is too far away. In case of high perforation, the boundary region is confined to the holes located directly along the boundary and the inner periodic region is stretched over almost the whole membrane. This analysis shows that boundary effects do influence the pressure profile. Consequently, Veijola's assumption that the perforations cells are independent of each other, i.e. the pressure profile is periodic, holds only true in the inner region of moderately perforated membranes or for highly perforated membranes. Thus, the larger the microstructure is and the more perforations the structure has, the less the influence of the boundary effects will be and the better the compact model by Veijola will agree with experiments. The same consideration holds true for the model by Bao: the more periodic the pressure profile is, the more justified is the integration of a constant loss rate across the perforated membrane. This is exactly what we see in Table 2 – the larger the microstructure is, the more accurate are the two compact models.

5 RESULTS AND DISCUSSION

The SQFD on three microstructures of different sizes and with different perforation levels was investigated experimentally as well as using two compact models and one mixed-level model. The mixed-level model showed very good agreement with the measured data with a maximum relative error of about 4 % at normal pressure. The compact models by Bao and Veijola showed acceptable agreement with errors of 12 % for the largest microstructure (A4), but errors exceeding 30 % for the smaller samples. An analysis of pressure profiles indicates that this error is due to boundary effects that are, in contrast to the mixed-level model, not accounted for in the compact models.

REFERENCES

[1] M. Bao, H. Yang, et al., J. Micromech. Microeng., 13, 795–800, 2003.
[2] T. Veijola, J. Microfluid Nanofluid, 2, 249–260, 2006.
[3] Hamrock, B., Fundamentals of Fluid Film Lubrication, McGraw-Hill, Singapore, 1994.
[4] T. Veijola, G. De Pasquale, A. Soma, J. Microsyst. Technol., 15, 1121–1128, 2009.
[5] G. De Pasquale, T. Veijola, et al., J. Micromech. Microeng., 20, 015 010 (12), 2010.
[6] G. Schrag and G.Wachutka, Sensors and Actuators A, 97-98, 193–200, 2002.
[7] Niessner M., Schrag G., et al., Sensors and Actuators A, 172 (1), 269-279, 2011.
[8] Weinberg M., Candler R., et al., Tech. Digest of the 15th Int. Conf. on Solid-State Sensors, Actuators and Microsystems (Transducers'09), 688–695, 2009.