Physically−Based Damping Model for Highly Perforated and Largely Deflected Torsional Actuators

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ABSTRACT

We propose a mixed level simulation scheme for squeeze film damping (SQFD) effects in microdevices, which enables the inclusion of damping effects in system level models of entire microsystems in a natural, physical−based, and flexible way. Our approach allows also for complex geometries and coupling to other energy and signal domains. Applying the methodology to torsional structures yields results which are in excellent agreement with FEM simulations, based on the 3D Navier−Stokes equations, thus demonstrating the quality of our approach. For highly perforated structures the number of holes must be reduced by merging of adjacent holes. With a view to deriving scaling laws for this merging procedure, we carried out systematic FEM simulations.

Keywords: mixed−level modeling, squeeze film damping, system simulation, torsional actuators, highly perforated devices

1 INTRODUCTION

The dynamic behaviour of MEMS components, such as, e.g. accelerometers, torsional mirrors and RF switches, is often strongly affected by viscous air damping effects. In order to include these effects in a device model, there are basically two strategies: On the one hand, heuristic damping terms may be introduced in the model as empirical fit parameters, without specific physical meaning and without the ability of scaling with the design dimensions. On the other hand, damping effects can be accurately analyzed by solving the highly complicated Navier Stokes equation (NSE). However, the second approach easily becomes prohibitive because of the excessive computational effort which is required, if couplings to different physical energy domains have to be included and/or if complex device geometries have to be treated. This is typically the case for surface−micromachined microdevices which exhibit highly perforated membranes as structural elements.

Since damping is an inherent and inevitable consequence of the operational principle of such complex device, the individual damping mechanism has also to be incorporated in system level models. This can be accomplished in an efficient but yet physically correct and accurate way by following the mixed−level approach, which has been proposed in [1] and will be extended to tiltable device structures in this work.

2 MODELING OF SQUEEZE FILM DAMPING

2.1 Mixed Level Damping Model

Under certain assumptions, SQFD can be described by the Reynolds equation, which follows from the NSE under certain simplifying and idealizing assumptions and is well−known from theory of tribology [2]. Based on this equation several methods have already been proposed which allow the modeling of SQFD by reduced order models on system level, but they are either restricted to simple and very special geometries and to the linear operation regime [3,4] or they just neglect geometrical effects (open border effects, perforations), which are not

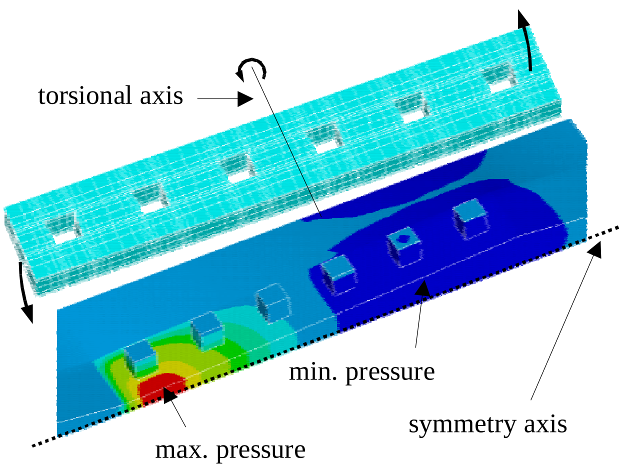

Fig. 1: Top: FEM model of the torsional actuator. Bottom: pressure distribution underneath the actuator at a left tilt.

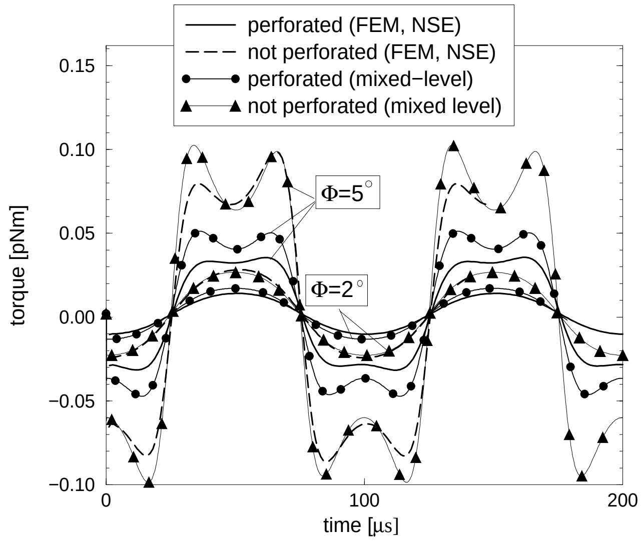

Fig. 2: Reactive torque of the torsional actuator with and without perforation. Comparison of NSE−based results with our mixed−level model.

covered by this simplifying approach [5].

The basic ideas of the applied methodology have been presented in [1]. The model is based on the Reynolds equation, which is solved by employing the Finite Network method. Physically−based compact models are added to correct for finite size effects and perforations in the structure. These models scale with all important design parameters and contain only a minimum set of well−understood fit parameters, which are determined from a small number of NSE−based FEM−simulations of simple basic structures (rectangular plates; plate segment containing one hole). No recalibration was done for the investigations in this work. (For details on the models and the calibration procedure see [6]).

In this work we extend this mixed level model to tilting motions in order enable also the simulation of torsional structures like micromirrors and micromechanical relays.

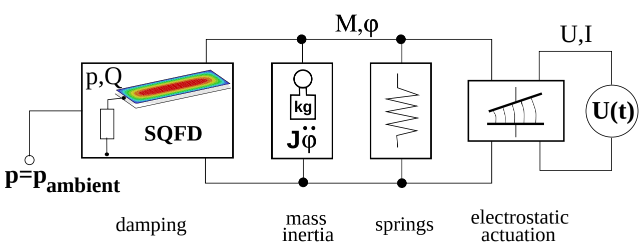

Fig. 3: System level model of an electrostatic torsional actuator. Damping is included as a mixed−level model.

2.2 Simulation Results

The method described above was applied to tiltable per−forated and non−perforated plates (with the device geometry and pressure distribution underneath the moving plate as obtained from NSE−based FEM; see Fig. 1).

The dynamical device behaviour calculated by this mixed level model has been compared with NSE−based FEM simulations (Fig.2) and shows a notably good agreement even for very large deflections up to the touch down of the plate (at a tilt angle of φ=6°), while the computation time can be reduced from days (FEM) to minutes (mixed−level model).

The mixed−level damping model can be straightforwardly combined with compact models of the torsional springs, the mass inertia and the electric circuit for the electrostatic actuation, so that we eventually arrive at a system level macromodel of the entire microsystem as displayed in Fig. 3. The compact models for the mechanical and electrical parts of the electrostatic actuator are described in [7]. Equipped with this macromodel, we are now able to study the dynamic behaviour of the device in a time−saving and cost−effective but still very accurate manner. This, in turn, allows the efficient analysis of design variations with respect to size and perforation of the actuator (Fig. 4).

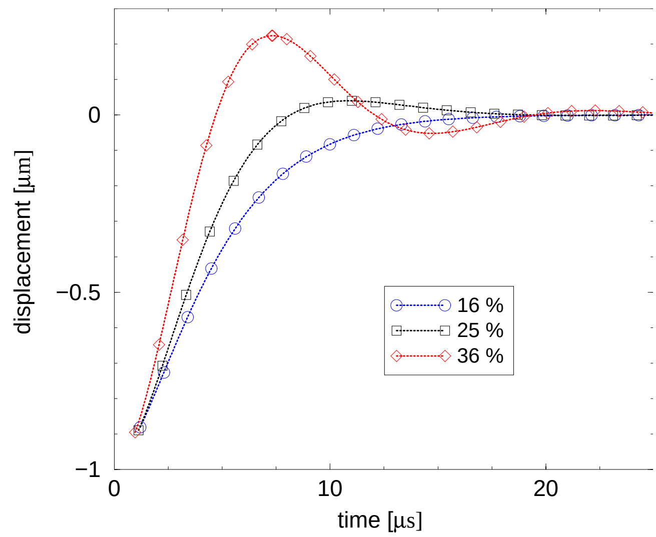

Fig. 4: System level simulation of the off−on switching of an electrostatic torsional actuator for different perforations (ratio of area of etch holes to area of the tiltable plate in %).

3 MODELING OF HIGHLY PERFORATED DEVICES

One has to realize, however, that industrial state−of−the−art devices such as the fast RF microswitch presented in [8] (and displayed in Fig. 5) contains a large, very densely

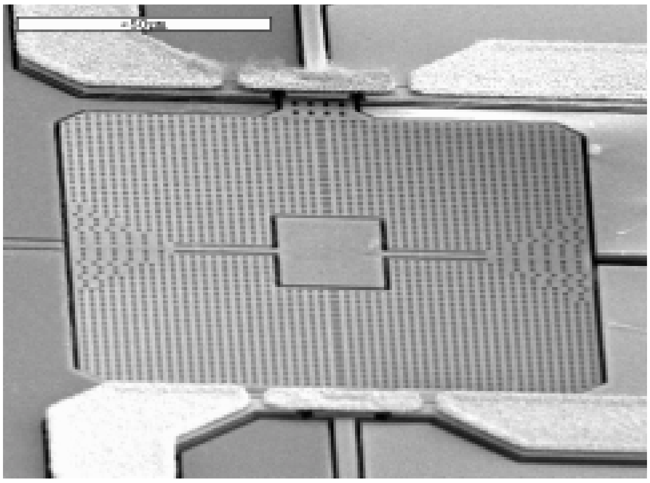

Fig. 5: SEM image of an electrostatic microswitch with over 2000 etch holes [8].

perforated, tiltable plate with several thousands of holes, and this constitutes a computational challenge again even for our macromodel. To keep the simulation time for design optimization at a reasonable level, it is necessary to reduce the degrees of freedom in the damping model by merging a certain number of holes into an equivalent lumped element. With a view to deriving scaling laws for this merging procedure, we carried out a sequence of systematic 3D−NSE−based FEM simulations, where we increased the number of etch holes, but with the ratio of perforation kept constant.
As teststructures we considered small perforated square plates (6 µm x 6 µm), which were driven in sinusoidal motion with elongation of up to 90% of the squeeze−film thickness. The damping forces acting on the moving structures were calculated for an increasing number of etch holes. The results of our investigations for these small plates with a relatively small number of perforations are displayed in Fig. 6. We find a general tendency, that the changes in the reaction forces with increasing number of holes are relatively small. This observation suggests that we may reduce the geometric complexity of the microswitch displayed in Fig. 5 by merging four holes into one single hole, ending up in mixed level models for three design variants of the switch containing now 500−750 instead of 3000 etch holes.
In this way, the reaction forces acting on the tilting device can be calculated within 10 to 15 minutes, while the simulation of the damping characteristics by means of FEM would be nearly impossible for this kind of densely perforated devices. The results for the three design variants obtained by mixed level simulation are shown in Fig. 7. From the results displayed in Fig.6 the damping coefficient for the three variants of the tilting microswitch can be extracted and included in very fast low order models. Alternatively the mixed−level model can be directly linked to a system−level model of the entire microsystem [9].
However, for further work, the merging of the holes should be critically revised with regards to larger plate dimensions and a higher number of holes, though this is rather difficult due to the exploding computational effort of the FEM simulations required.
Current work focusses on systemizing the merging procedure for densely perforated devices to derive scaling laws for further order reduction of the damping models. This will allow fast and efficient design studies on system level, which are also applicable to extremely high perforated microdevices

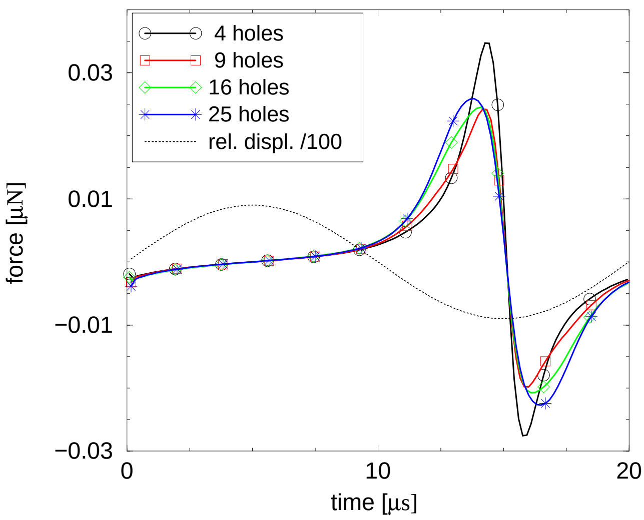

Fig. 6: Reactive force on a square plate with 25 % perforation during harmonic actuation up to 90% of the squeeze−film thickness.

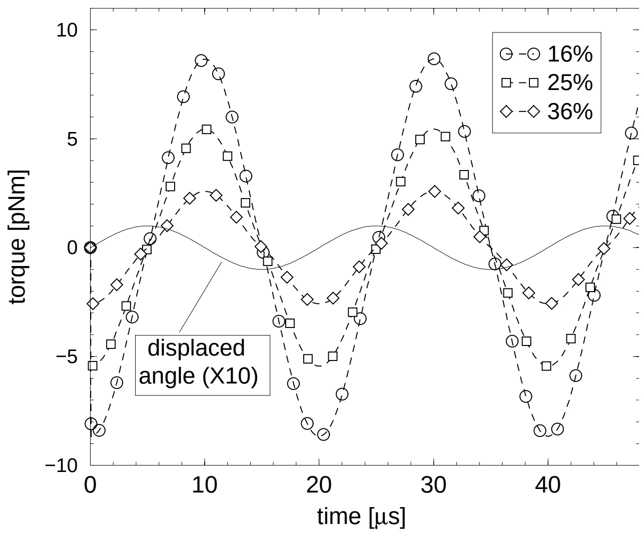

Fig. 7: Damping force for three different types of perforations.

4 CONCLUSIONS

We demonstrated that the mixed level approach for the modeling of squeeze film damping effects in microsystems derived in [1] and [6] can be successfully extended to tilting microdevices. The results obtained with this damping model for tilting perforated and non−perforated teststructures are in good agreement with Navier−Stokes−based finite element simulations. It is notable that the compact models accounting for edge effects and perforations, which were derived for simple basis structures [1,6], had not to be recalibrated to perform these calculations.

The simulation of a complex microswitch fabricated by surface micromachining shows that even devices with a very high number of perforations − in our case some hundreds to thousands − can be treated in a very detailed and accurate manner by this mixed level approach in reasonable computation times of some minutes to one hour.

For densely perforated structures the order of the model can be further reduced by scaling laws deduced from systematic finite element simulations carried out for moving micromechanical plates with varying perforations or − for very fast low order system models − to extract damping constants directly from a detailed mixed level model as mentioned above.

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