High-Fidelity and Behavioral Simulation of Air Damping in MEMS

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ABSTRACT

The paper presents simulations of air damping in MEMS, including squeeze-film and viscous dissipation, using different level models: 3D numerical solution of Navier-Stokes equations (using CFD-ACE from CFDRC), and circuit/behavioral model (in SPICE and Saber/MAST formats). Results of the squeeze film compact model, based on an equivalent circuit, agree very well with the 3D results even for very large amplitudes of plate motion (up to 90% of the nominal gap), accompanied by significant changes of pressure (up to 15 times bigger than the static ambient pressure). All previous squeeze film simulations published by other authors were limited to small amplitudes and small pressure changes only. To derive behavioral models for torsional micromirrors, comb-drive resonators, and moving plates with holes, a comprehensive analysis of shear and squeeze forces acting on moving MEMS elements has been performed.

Keywords: MEMS, air damping, squeeze film, 3D simulation, circuit/behavioral models

1. INTRODUCTION

MEMS devices are characterized by very small gaps between the moving elements and the fixed parts, hence in atmospheric pressure the air damping dominates the energy dissipation mechanisms in mechanical sensors and actuators. Many authors have already analyzed the air damping in MEMS: for example, squeeze-film behavior between plates [1, 2], gas damping for micromirrors [3, 4], and viscous damping for laterally oscillating microstructures (comb drives) [5, 6]. However, for the squeeze-film damping, the solutions were shown only for small motion and pressure amplitudes, which may be not necessarily true in real MEMS applications. The models of the viscous damping for laterally oscillating microstructures were mostly based on the assumption of Couette flow under the moving plate, extended later by Stokes flow model above the resonator [5, 6]. The proposed analytical formulae were not sufficiently general, and required special fitting coefficients to match experimental data [7].

This paper presents simulations of air damping in MEMS for large displacements, including squeeze-film damping for plates and mirrors, as well as viscous dissipation for laterally oscillating microstructures. Different level models are used: a 3D high-fidelity transient solution of full Navier-Stokes equations, and compact/behavioral model based on equivalent circuit. Our compact model of squeeze-film damping was implemented in SPICE and Saber/MAST formats. Comparisons between the 3D and compact model results have been performed for broad range of frequencies, amplitudes, operating pressures, and motion patterns, and sample results are discussed in Section 2. The paper presents the squeeze film behavior for very large amplitudes, up to 90% of the nominal gap thickness, accompanied by significant changes of pressure (up to 15 times bigger than the static ambient pressure). These results show that the assumptions of small pressure changes are not valid for large displacements !

To derive behavioral models for torsional micromirrors, comb-drive resonators, and moving plates with holes, a comprehensive analysis of shear and squeeze forces acting on moving MEMS elements has been performed. Two test problems were selected for the numerical experiments: a solid plate moving over a substrate between side walls (like comb-drive stator), and a moving plate with holes (Figure 1). An analysis of air damping forces acting on the plate moving in parallel to the substrate is presented in Section 3, while example results of damping forces on a tilting plate (micromirror) are shown in Section 4.

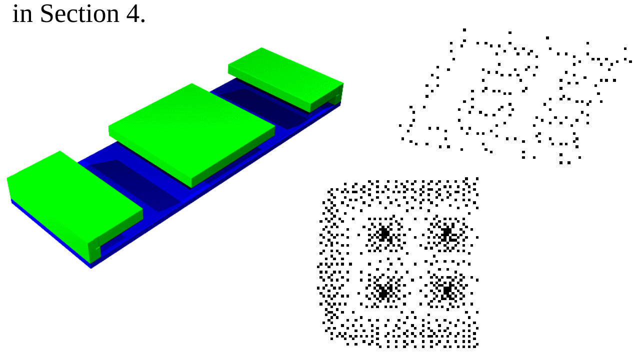

Figure 1: Vehicles for the numerical experiments: moving solid plate and plate with holes.

2. SQUEEZE FILM DAMPING

When a gas (air) film between two closely spaced moving plates is squeezed, it produces forces that oppose the motion of the plate. The viscous and compressibility effects dissipate the energy of the moving plate, which is known as squeeze-film damping. Several authors have already analyzed the squeeze-film behavior, but all the solutions have been shown only for small amplitudes of the motion. An analytical solution of the linearized compressible isothermal Reynolds equation was proposed by Blech in [10], under the assumption that the motion of the plates and the pressure variations are small. On the basis of this solution, an equivalent-circuit model of squeeze-film damping was developed by Veijola *et al.* in [1], realized with a ladder of RL (resistor and inductor) branches. This model was also derived with the same assumptions of small amplitudes of motion and small pressure changes, and for such conditions a good agreement of the circuit model with measurements was demonstrated in [1]. A modification of the R and L values in the equivalent circuit, as nonlinear functions of displacement, was also proposed in [1], but no large-amplitude results or verification were shown.

We have implemented the equivalent-circuit model of squeeze-film damping in SPICE and Saber/MAST formats [8]. The compact model has been verified by comparison with 3D high-fidelity simulation results, for a broad range of frequencies, amplitudes, operating pressures, and motion patterns, including first published results for very large amplitudes and pressure changes.

The plates with holes do not have a simple analytical solution for squeeze film forces, like in the case of parallel rectangular full plates. Therefore, a series of high-fidelity 3D simulations is needed to generate a reduced model of air damping for plates with holes, for system-level simulations.

High-Fidelity 3D Gas Flow Model

Computational simulations of the unsteady flow dynamics in the squeeze film were performed using CFD-ACE program from CFDRC [11]. The code solves three-dimensional (3D), unsteady Navier-Stokes (N-S) equations on moving/deforming hexahedral grids. To ensure strong temporal and spatial conservation of scalar and vector quantities the code uses the integral formulation of N-S equations complemented with the space conservation principle:

$$\frac{d}{dt} \; d \; + \; _{s}\vec{V}_g \, ?d\vec{s} \tag{1}$$

where is an arbitrary moving control volume, s is the surface of , $\vec{V}$ is the absolute fluid velocity vector. The mass and momentum conservation laws for arbitrary fluid are written on a moving control volume as:

$$\frac{d}{dt} \; \rho d \; + \; _{s}\rho\left(\vec{V} - \vec{V}_g\right)?d\vec{s} = 0 \tag{2}$$

$$\frac{d}{dt} \; \rho\vec{V} d \; + \; _{s}\rho\vec{V}\left(\vec{V} - \vec{V}_g\right)?d\vec{S} = \; _{S}\vec{\sigma} \, ?d\vec{S} \tag{3}$$

where $\vec{\sigma}$ is the second order stress tensor.

The above equation set was solved using second order accurate finite volume numerical method and segregated solution procedure [12]. Ambient pressure conditions were imposed on open sides of the film. Figure 2 illustrates the air flow pattern in the middle of the squeeze film and the pressure on the surface of the moving plate with 8 holes.

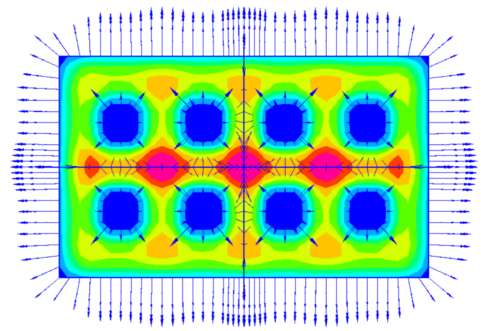

Figure 2: Calculated gas flow pattern and the pressure contours in the squeeze film under plate with holes.

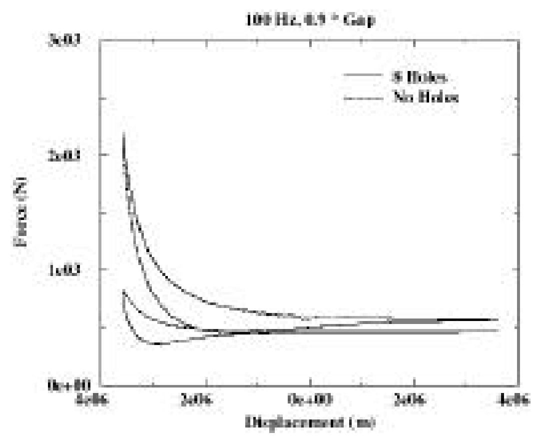

Figure 3: Squeeze-film force acting on the plate with 8 holes and without holes, as function of displacement.

Circuit and Behavioral Models Compared to 3D Numerical Simulations

The equivalent RL model from [1] was implemented in our case first in SPICE, in which the nonlinear *L* and *R* elements in the equivalent circuit had to be represented by nonlinear controlled voltage and current sources [8]. To verify the circuit model for large amplitudes, comparisons with the 3D Navier-Stokes solutions were done.

For low frequencies, like 100 Hz, the nonlinear compact model results agree very well with 3D results (Fig. 4a), even for the very large amplitudes of plate motion, accompanied by significant changes of pressure (3-fold increase to ambient pressure). For higher operating frequency of 100 kHz (Fig. 4b) and displacement 0.9 of the gap, the resulting relative dynamic pressure value is about 15 times bigger than the static ambient pressure. The agreement between circuit and 3D results for the high frequency is not as good as for low frequencies, but the shape of characteristics is preserved and we believe the equivalent-circuit RL model still can be used even for high frequencies, after some parameter fitting.

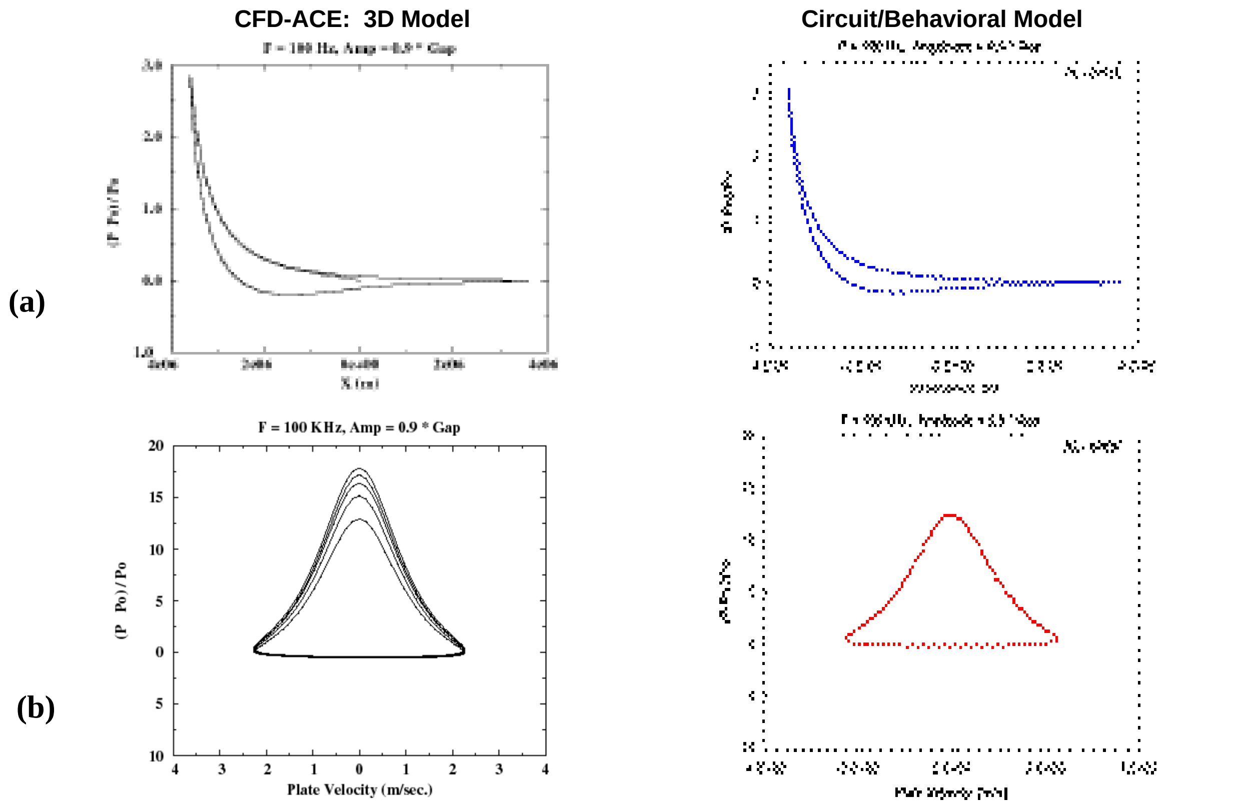

Figure 4: Squeeze film relative pressure changes with respect to static ambient pressure, for plate oscillations with amplitude equal to 90% of the nominal gap height: **(a)** as a function of **displacement**, and frequency **100 Hz;** **(b)** as a function of **plate velocity**, and oscillation frequency **100 kHz**.

The equivalent-circuit model of the squeeze film behavior has been also implemented for the Saber simulator with templates written in MAST, an analog hardware description language [8]. The Saber/MAST version of the behavioral squeeze film model uses directly mechanical quantities (Figure 5): position as input (across variable) and damping force as output (through variable), which is compatible with hierarchical representation for system-level design of MEMS, like the NODAS methodology developed at Carnegie Mellon University [9].

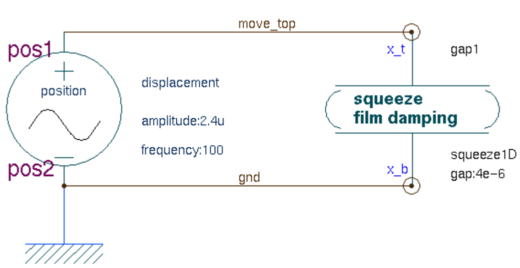

Fig. 5. Squeeze film behavioral model in Saber, with mechanical displacement source.

3. LATERAL MOVEMENT DAMPING

To be able to extract the basic dependencies for deriving a behavioral model for lateral air damping, a series of high-fidelity 3D simulations has been performed using CFD-ACE, for the rectangular plate moving horizontally over a flat surface (Figure 1). The component forces acting on particular walls of the plate, i.e. shear forces (on bottom surface and top surface) and side squeeze forces (side walls in the direction of movement) were extracted from the results of the simulations, and plotted in time. The 3D transient simulations, comprising solution of the full set of Navier-Stokes equations, were performed for a sinusoidal movement of the plate, for several frequencies of movement ranging from 1kHz to 100MHz (Figure 6).

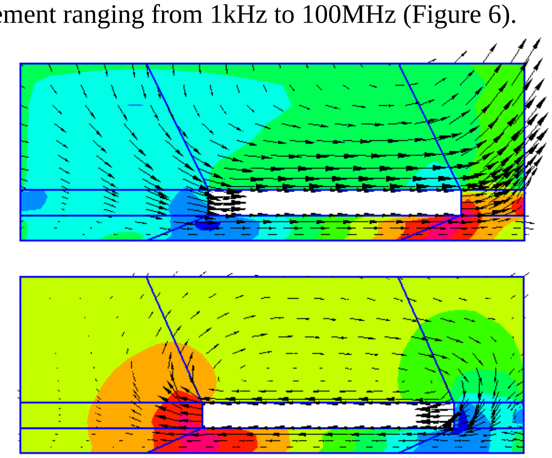

Figure 6: 3D simulation of air damping forces on a plate: air pressure (colors), and flow velocity (vectors).

Example damping force characteristics are shown in Figure 7. The obtained characteristics of shear and squeeze forces as functions of frequency will be used subsequently to develop a comprehensive behavioral model for the air damping phenomena. It was also noticed that for high frequency oscillations, thermal effects are quite significant, and they will be presented in forthcoming publications.

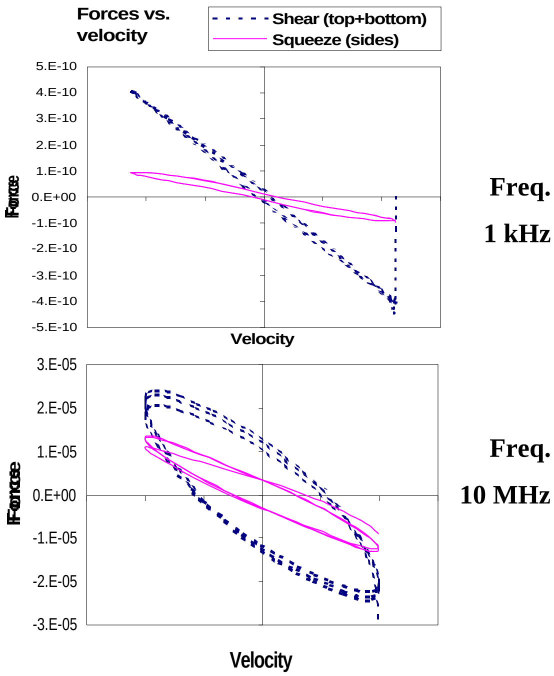

Figure 7: Shear force and side squeeze forces as functions of velocity of the laterally oscillating plate.

4. TILTING MICROMIRRORS

The air damping forces acting on torsional or tilting micromirrors are also a combination of squeeze and shear forces, though the squeeze film damping seems to be the dominant phenomenon [3]. We have used the torsion mirror structure data from [3] for 3D numerical simulations of air damping characteristic of a tilting plate (Fig.8), as functions of velocity and displacement, for various frequencies and signal shapes. An example of the damping torque dependence on the plate (mirror) velocity, for frequency 1kHz, is shown in Figure 9. Such results will be also used for generation and verification of behavioral models.

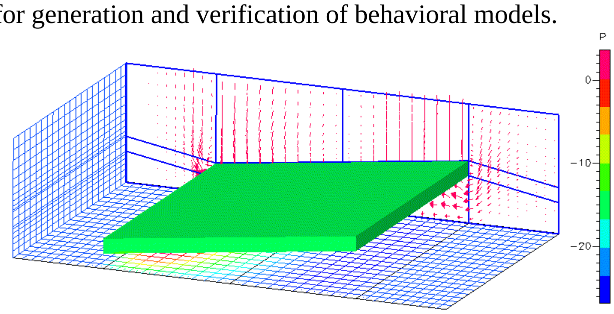

Figure 8: 3D simulation of air damping forces on a tilting plate: air pressure (colors), and flow velocity (vectors).

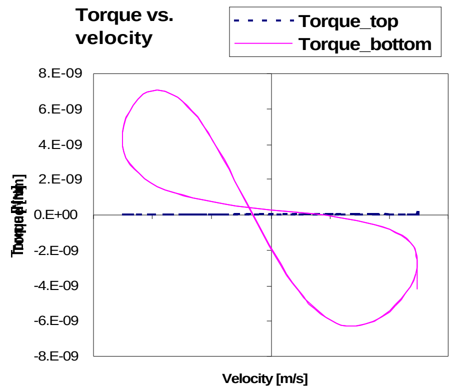

Figure 9: Torque characteristics of the tilting plate, oscillating with frequency 1kHz.

ACKNOWLEDGEMENT

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