

Rarefied Flow Solver in MEMOSA-FVM: Verification, Validation, and Application to Microscale Damping

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Motivation and Objectives

Motivation: The large variation in life cycles for varying operating pressures necessitates the proper usage of damping models for accurate predictions.

Main objectives: Develop unsteady rarefied solver integrated with the finite-volume method (FVM) MEMS Overall Simulation Administrator (MEMOSA) and apply it to study micro-scale damping.

Boltzmann equation
$$\frac{\partial f}{\partial t} + v \cdot \frac{\partial f}{\partial r} = \int_{-\infty}^{\infty} \int_0^{4\pi} (f^* f_1^* - f f_1) v_r \frac{d\sigma}{d\Omega} d\Omega dv_1$$

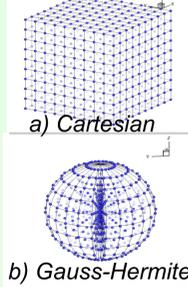
Model Kinetic equation
$$\frac{\partial f}{\partial t} + c_x \frac{\partial f}{\partial x} + c_y \frac{\partial f}{\partial y} + c_z \frac{\partial f}{\partial z} = -\frac{f - f_\gamma}{\tau}$$

ES-BGK Model

$$f_\gamma = \exp(\alpha_i \cdot V) \quad V = [0, -u'^2, u', -v'^2, v', -w'^2, w', u'v', v'w', w'u']$$

$$u' = c_x - u, v' = c_y - v, w' = c_z - w \quad \frac{1}{\tau} = \text{Pr} \frac{P}{\mu}$$

Fig. 1 Velocity Meshes



Verification Test: Couette Flow with Slip

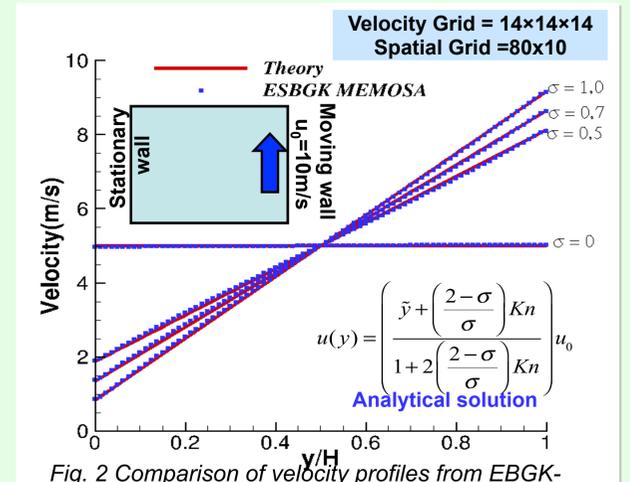


Fig. 2 Comparison of velocity profiles from EBGK-MEMOSA with analytical solution

Full 3D-3V Simulations: Damping on PRISM Gen 5 Device During Pull-in

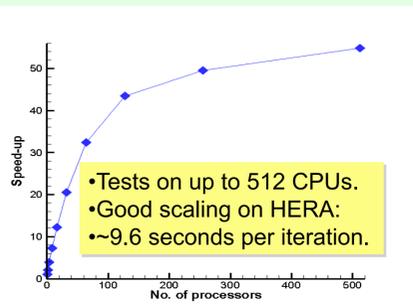


Fig. 3: Parallel efficiency of 3D using spatial domain decomposition.

- 3D simulations of PRISM device damping near pull-in were performed.
- The beam velocity was obtained from the PRISM coarse-grained beam dynamics model and specified as a boundary condition for the ES-BGK solver.
- 3D spatial mesh was deformed by "Moving-mesh" model using given deflection.

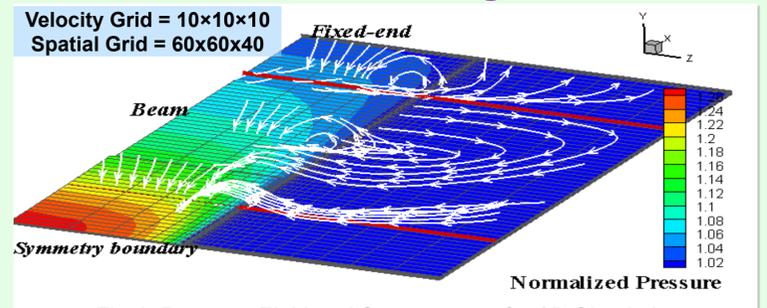


Fig. 4: Pressure Field and Streamtraces for 3D Simulation

Nonlinear Effects for Microbeam Damping at Large Displacements

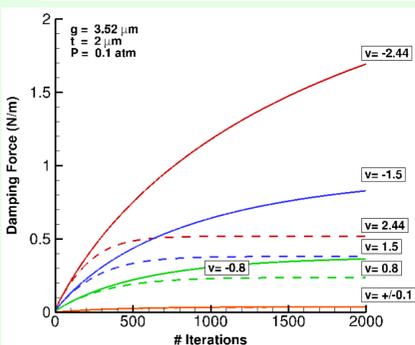
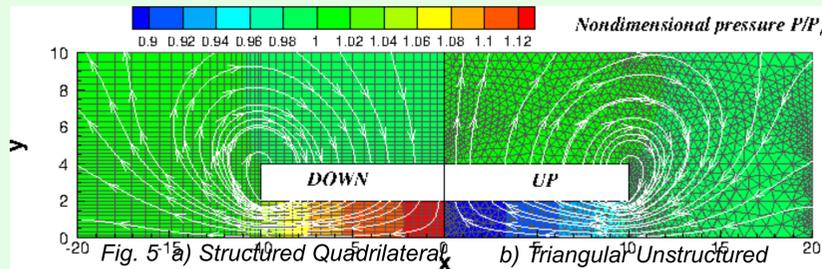


Fig. 6: Damping force comparisons for varying beam velocities

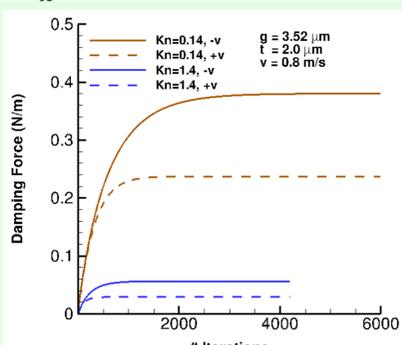


Fig. 7: Convergence rate comparisons for varying Kn at 0.8 m/s.

- Beam velocity effects on the pressure fields and resulting damping force predictions are performed.
- At lower velocities of 0.1m/s the difference in damping force between upward and downward moving beams is 5% and increases to over 200% for beam velocity of 2.44m/s.
- For a constant velocity magnitude of 0.8m/s, this difference changes from 60% to almost 90% when the pressure is reduced by an order of magnitude.
- Convergence rates are much lower for beams moving downward with high velocities

In summary, direction of motion of beam should be taken into account while building/using damping models in design of MEMS devices .

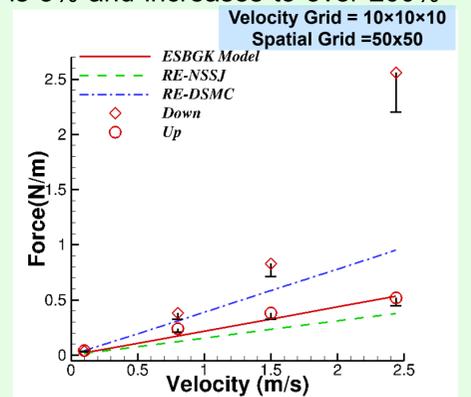


Fig. 6: Damping force for upward and downward moving beam simulations at different velocities and comparison with popular linear models . Ref [1-3]

Free-Cantilever Damping

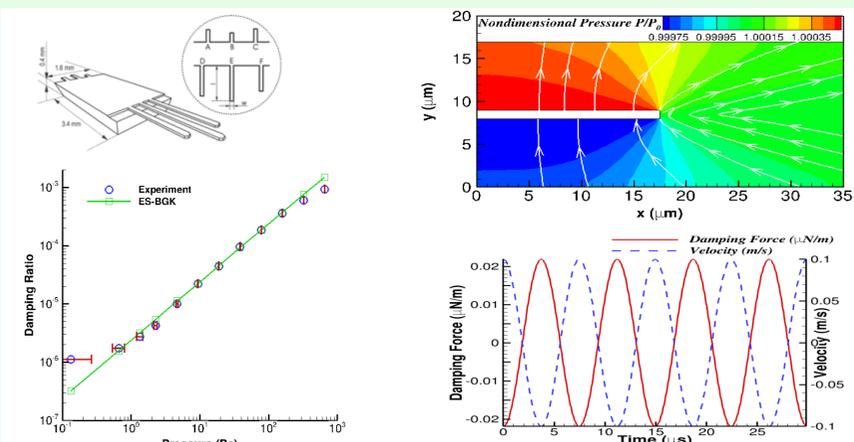


Figure 8 a) Damping factors from 2D unsteady damping simulations and comparison with experiments Ref.[4], b) pressure contours and streamlines for $P_0=0.66\text{Pa}$ and c) variation of damping force with time over 4 cycles

References

- [1] Guo, X. and Alexeenko, A., "Compact Model of Squeeze-film Damping Based on Rarefied Flow Simulations," *JMM* (2009).
- [2] Veijola, T., "Compact Models for Squeeze-film Dampers with Inertial and Rarefied Gas Effects," *JMM* 14, 2004.
- [3] Gallis, M. and Torczynski, J., "An Improved Reynolds-equation Model for Gas Damping of Microbeam Motion," *JMEMS* 13 2004.
- [4] R. Bidkar et al., "Unified Theory of Gas Damping of Flexible Microcantilevers at Low Ambient Pressures," *APL*, Vol. 94, 163117 (2009).

Conclusions

- Solver has been verified for unsteady 0D manufactured and steady 1D analytical solutions.
- Solver has also been compared with steady ESBGK solver for 2D gas damping problems
- Extension of the ES-BGK code to simulate 3D gas damping has been demonstrated
- Demonstrated parallel scaling up to ~50 on 512 processors.
- Contrary to the frequently made linearity assumption that the direction of micro-beam motion does not affect the squeeze-film damping force, we show that the difference can vary from as little as 5% for low beam velocities of 0.1m/s to 200% at 2.4m/s.
- A preliminary validation of the unsteady rarefied gas damping simulations has been performed by comparison with experimental measurements for a free-cantilever.