Air Damping of Oscillating MEMS Structures: Modeling and Comparison with Experiment

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Abstract

Various MEMS devices, resonators and sensors are designed to operate in air and viscous fluids. Excessive air damping can be detrimental to the performance of oscillating MEMS components. Quantitative evaluation of the air damping is, therefore, required already during the design stages to obtain accurate predictions of the device performance. The interaction of fluid flow with moving structures is complex such that analytical approximations of the damping coefficient are available only for simple structures. More complex systems involving air flow between structures moving with respect to each other and in proximity to stationary objects (such as structures in pre-etched cavities or angular comb-drive scanning mirrors), typically require simulations to reliably evaluate the air damping. The analysis of air damping in several complex systems in this study was performed using Fluid-Structure Interaction interface of COMSOL Multiphysics®. The simulated and experimental performance of the following systems was evaluated and compared: two types of out-of-plane cantilevers, in-plane and out-of-plane tuning forks, and a torsional mirror (Figure 1). A full three-dimensional damping analysis is computationally very expensive and time-consuming. Instead, a simpler two-dimensional analysis of the damping per unit length of the structures and as a function of initial displacement was performed (Figure 1). Such an approximation neglects edge effects and, in case of a bending cantilever, also the rotary motion of the beam cross-section. The validity of the approximation is, however, justified by the consistency of simulated and experimental results. The simulations in time domain were initiated by displacing the cross-sections of the structures by initial amplitude A from the equilibrium position (or tilting them by angle A). Due to the restoring forces or torques, the simulated systems began to oscillate. The oscillation amplitude decayed due to the interaction with air as the simulations progressed in time, and the Q-values were estimated from the logarithmic decrement of amplitude (Figure 2). To further simplify the simulations, the restoring spring forces/torques due to the springs' deformation were replaced by numerical forces/torques. The restoring force/torque was defined as, e.g., boundary load $-k(A+u)$, where k is the spring constant per unit area (adjusted to result in the required resonance frequency of the system), and u is the structural displacement of the centre of mass. The numerical springs effectively replaced the action of actual restoring forces thus eliminating the need to simulate the structural deformations and reducing the simulation complexity. Some of the experimentally measured Q-values of selected systems are compared with simulated results in Figure 1. The good agreement of 2-19% validates the applicability of the simplified 2D model and proves its feasibility for estimation of the air damping in MEMS systems.

Figures used in the abstract

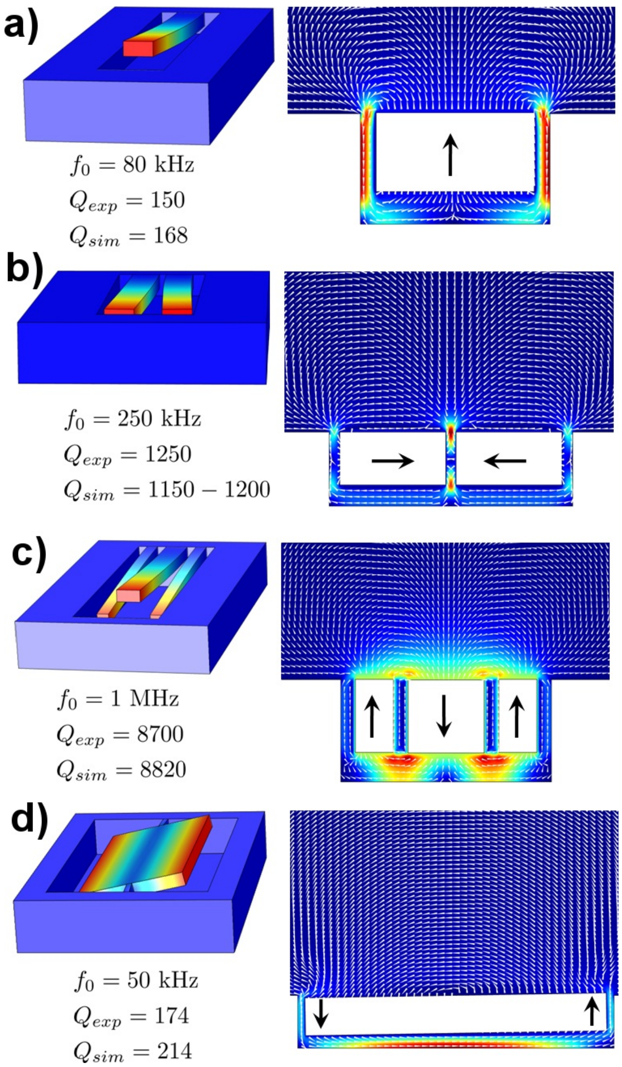

Figure 1: Simulation of air damping in various resonating MEMS systems using a simplified 2D model with numerical ”springs” that replace the deformable flexures and generate corresponding restoring forces. Schematic deformation of the system in 3D, air flow simulation time-snapshot in 2D, resonance frequency, simulated and experimentally measured Q-values are presented for each system. a) Out-of-plane cantilever. b) In-plane tuning fork. c) Out-of-plane tuning fork. d) Torsional mirror.

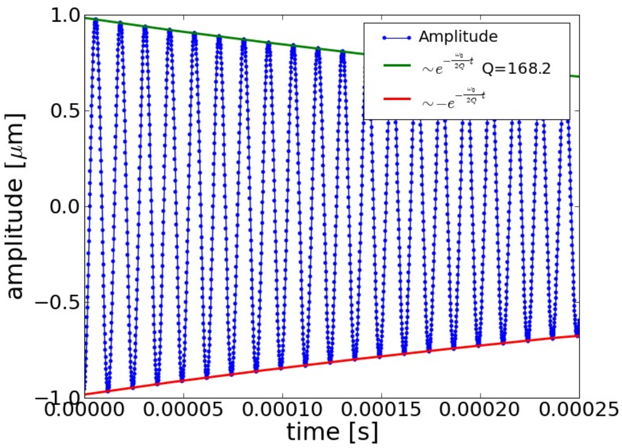

Figure 2: Time-domain simulation of a cantilever's (from Figure 1a) tip displacement initially displaced by 1 µm from the equilibrium position. Due to the interaction with air, the amplitude decays. The Q-value can be obtained from the logarithmic decrement of the amplitude.