Squeeze-film damper design with air channels: experimental verification

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Abstract

The experimental evaluation of damping-improved parallel-plate geometries is reported in this paper. An improved damper geometry with air channels was developed to address contradictory design constraints: large sensing parallel-plate area is desirable for a significant readout capacitance as well as reduced damping coefficient. Damping coefficients were measured at different gaps in conventional parallel-plates MEMS and in parallel-plates with air channels. The inertial masses of the fabricated structures were pulled-in and released. From the return to rest position trajectory, the damping coefficients, at each point, were extracted. Results show a significant damping decrease in parallel-plates with air channels without visible reduction in the capacitance value.

Keywords: Squeeze-film damping; air channels; MEMS capacitive sensing.

1. Introduction

Damping has a major impact on the noise and dynamic behavior of MEMS devices. When the distances between movable parts are just a few micrometers, fluid (usually air) is trapped, resulting in squeeze-film damping. In the case of inertial MEMS devices, the damping forces are not only determining the dynamic response but also the mechanical-thermal noise of the system [1, 2]. When designing in-plane capacitive devices (sensor, actuator or both), typical damper design involves a trade-off between sensitivity, response time and noise. A typical example is the case of a capacitive accelerometer: if a higher capacitive sensitivity is needed, extra capacitor plates result in extended response time and higher mechanical-thermal noise [2]. In some cases, where high-quality factors are desirable (e.g. for gyroscopes), vacuum encapsulation is used at the cost of more complex fabrication processes.

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An improved damper geometry for in-plane-movable parallel-plates structures, which enables the reduction of the squeeze-film damping coefficient while maintaining a large capacitance, has been previously introduced [3]. The design solution introduced air channels, or wells, in the parallel-plates geometry, so that the air flow will be relaxed.

In the next sections the air channel geometry is described. Then, fabricated structures with improved and conventional damper geometry are presented and the damping coefficients are measured and compared.

2. Squeeze-Film Damper with Air Channels

Parallel-plates under oscillation give origin to damping forces, due to gas trapped between the plates, that depend not only on the gas pressure and viscosity, but also on the geometry. It seems intuitive that if gas channels are introduced along the length of the parallel-plates, in the direction of motion, the pressure differences caused by the trapped air will be smaller resulting in a controlled decrease of the damping forces.

The improved geometry for parallel-plate dampers is presented in Fig. 1. The figure shows a small section of a parallel-plate configuration. The underlying idea is to introduce small gas channels within the capacitor arms to improve the gas flow. As the flow is improved, less gas is trapped during oscillations, less pressure is generated, and therefore there is a reduction of the damping coefficient [3]. Since these air channels are small, as compared to the arm length, they can effectively reduce the damping forces without affecting the capacitance value.

Fig. 1. Schematic of an air channel in a comb finger.

3. Fabricated MEMS Structures

The two different MEMS structures (Fig. 2) used to experimentally validate damping reduction were fabricated using the SOIMUMPs micromachining process from MEMSCAP [4]. Both structures include a symmetrical inertial mass, suspended on 4 bi-folded springs with parallel-plate capacitors having 2.25 μm gap (Table 1). The inertial mass can move up to 2 μm to each lateral direction. The main difference between the two structures is the squeeze-film damper design – one (S1) has conventional parallel-plates, while the other (S2) has an improved design with air channels. Each damper (fixed/movable arm pair) has 10 air channels implemented (5 on each arm) with the dimensions specified in Table 1. The structures have a different number of comb fingers, which does not impair direct comparison since damping in conventional parallel-plates is proportional to the number of comb fingers.
Fig. 2. Microscope pictures of the fabricated structures (a) S1 and (b) S2 with detail showing air channels, folded spring and stoppers.

Table 1. Main modeled design parameters of the structures S1 and S2.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>S1</th>
<th>S2</th>
</tr>
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<tbody>
<tr>
<td>Mass ((m))</td>
<td>0.171 mg</td>
<td>0.167 mg</td>
</tr>
<tr>
<td>Spring coefficient ((k))</td>
<td>4.46 N/m</td>
<td>4.46 N/m</td>
</tr>
<tr>
<td>Zero-displacement gap ((d_0))</td>
<td>2.25 µm</td>
<td>2.25 µm</td>
</tr>
<tr>
<td>Zero-displacement actuation capacitance</td>
<td>0.175 pF</td>
<td>0.349 pF</td>
</tr>
<tr>
<td>Zero-displacement sensing capacitance ((C_0))</td>
<td>1.10 pF</td>
<td>2.21 pF</td>
</tr>
<tr>
<td>Damping coefficient ((b)) gap=(d_0)</td>
<td>0.654 mNs/m</td>
<td>1.31 mNs/m (if without channels)</td>
</tr>
<tr>
<td>Damping coefficient ((b)) gap=(2/3)(d_0)</td>
<td>1.07 mNs/m</td>
<td>2.14 mNs/m (if without channels)</td>
</tr>
<tr>
<td>L_A</td>
<td>4 µm</td>
<td></td>
</tr>
<tr>
<td>L_B</td>
<td>10 µm</td>
<td></td>
</tr>
<tr>
<td>W_A</td>
<td>3 µm</td>
<td></td>
</tr>
<tr>
<td>W_B</td>
<td>6 µm</td>
<td></td>
</tr>
<tr>
<td>Gap ((d_0))</td>
<td>2.25 µm</td>
<td></td>
</tr>
<tr>
<td>Arm length</td>
<td>500 µm</td>
<td></td>
</tr>
</tbody>
</table>

4. Experimental Procedure and Results

Firstly the capacitive readout circuit was calibrated (Fig. 3) by applying increasing acceleration values and monitoring the circuit output. From this procedure the actual stiffness coefficients were also retrieved (3.68 N/m for S1 and 3.87 N/m for S2). Afterwards, the structures were electrostatically actuated to induce full-gap displacement of the inertial mass. The applied voltage was then removed and the trajectory of the inertial mass back to its rest position was monitored. The dynamics governing the movement is described with a simple 2\(^{nd}\) order differential equation. The initial conditions were calculated from the previous positions, while the damping coefficients were computed from the time series of position measurements.

Fig. 3. Capacitive readout circuit calibration results
The results were compared to the expected damping coefficients obtained from a compact model for micromechanical squeeze-film dampers that includes rarefaction and border effects [5]. The conventional damper was modeled with less than 10% error for small displacements, but for smaller gaps more errors/deviations are observed.

The number of parallel-plates is doubled in S2 compared to S1, which translated into a capacitance gain on the sensing electrodes from 0.183 pF to 0.316 pF, leading to a higher readout performance. Nevertheless, Fig. 4 shows similar values for the damping coefficients of the two structures. This proves that the air-channels method is a suitable design approach to increase capacitance while keeping an optimum damping coefficient.

![Fig. 4. Damping results from the structures with (a) conventional damper and (b) with air channels. The featured analytic values assume no air channels, since no models are available for this geometry.](image)

5. Conclusions and Future Work

The damper geometry with air channels proved effective on reducing damping. Furthermore, no significant reduction of the capacitance value was observed. The proposed geometry can be particularly useful in the design of inertial sensors, since it allows improving current devices with extra sensitivity and better noise performance.

Additional tests are needed with different channel geometries, in order to evaluate how the channels dimensions affect damping and provide ground for a new damping model to be established.

Acknowledgements

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References