Characterization of a pull-in based μg-resolution accelerometer

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Abstract

The pull-in time of electrostatically actuated parallel-plate microstructures enables the realization of a high-sensitivity accelerometer that uses time measurement as the transduction mechanism. The key feature is the existence of a metastable region that dominates pull-in behavior, thus making pull-in time very sensitive to external accelerations. Parallel-plate MEMS structures have been designed and fabricated using a SOI micromachining process (SOIUMUPS) for the implementation of the accelerometer.

This paper presents the experimental characterization of the microdevices that validates the concept and the analytical models used. The accelerometer has a measured resolution of 0.25 μs/μg and an estimated mechanical-thermal noise of 2.8 μg/√Hz. Since the bandwidth of the sensor is directly related to the pull-in time (BW = 2/\pi \tau\text{pi}), the total measured noise floor of 400 μg (110 μs) suggests that the main noise source comes from the building vibrations.

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1. Introduction

State-of-the-art capacitive accelerometers have already demonstrated sub-μg resolution devices, with the total noise floor threshold being currently set on 230 ng/√Hz [1]. The accelerometer described in [1] was fabricated using modified and dedicated micromachining procedures which require a long and difficult path towards commercialization.

The concept of a μg-resolution accelerometer based on time measurement has been introduced in [2]. This accelerometer uses the pull-in time measurement of microfabricated closed-loop operated structures as the detection mechanism. Repeatedly bringing the microstructure to pull-in (actuating with voltage \( V_{\text{act}} = \alpha V_{\text{ps}} \), \( \alpha \approx 1 \)) while measuring the pull-in time, enables the measurement of external accelerations. The advantages of this approach are the low-noise (the non-mechanical noise is set primarily by the resolution of the time measurement, and therefore, the only noise source is the mechanical-thermal noise) and the low requirements for the capacitive sensing circuit.

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Micromachined structures to implement this accelerometer concept can be fabricated using standard commercially available fabrication processes. The devices presented here have been fabricated in a SOI process [3].

2. Pull-In Accelerometer

The underlying physical principle for the accelerometer setup is the high sensitivity of the pull-in time to external forces in electrostatically operated micromechanical devices [2]. A detailed study of the pull-in dynamic transition has been presented in [4] and the existence of a metastable region during a pull-in transition has been demonstrated in overdamped micromechanical devices. The presence of very small forces can change the overall pull-in time and these characteristic has been used in [5] to measure and characterize the mechanical-thermal noise in MEMS devices.

Using the pull-in time as the sensing mechanism requires for the implementation of functionalities in the mechanical domain, rather than the conventional direct transduction, and signal processing in the electrical domain. Since the non-mechanical noise is set primarily by the resolution of the time measurement (which can be very high – a few ns) there is a huge potential for the realization of high sensitivity, low-noise accelerometers.

A block diagram of the proposed time-based accelerometer is shown in Fig. 1. The core of the microsystem is a parallel plate microstructure with separate sensing and actuation electrodes. The microdevice is actuated by a square wave generator whose signal period must be larger than the nominal pull-in time (the time taken to reach pull-in at zero g acceleration). This guarantees that the measurement of the full pull-in transition time is performed. The capacitive changes of the microdevice are converted to a voltage by a front-end readout circuit. Since the changes in capacitance are quite large (considering nearly full gap displacements), the capacitive readout specifications are low in terms of resolution and noise which is a competitive advantage to the conventional direct transduction and signal processing in the electrical domain approach. Following the capacitive transduction, the signal is fed to a comparator, and as soon as a threshold is reached (nearly full gap), the time measurement is stopped and ground is applied to prevent the movable electrode to reach the counter-electrode. Using this preventive measure, the movable electrode returns to his rest position increasing the system’s reliability (the movable structure doesn’t reach the counter-electrodes or protective stoppers).

![Fig. 1. Microaccelerometer block diagram](image)

Finally, a time counting mechanism is used to measure the pull-in time, counting the time elapsed from rising edge of square wave to rising edge of comparator output. The pull-in time changes are proportional to the external acceleration sensed by the accelerometer.

Operation of the microstructure in the meta-stable region raises some design constraints. Since the micromechanical structure should be sufficiently damped (to present the meta-stable behaviour) and the mechanical-thermal noise depends on the damping coefficient, one must be careful when designing the damper. Therefore, design of the damper is very important as it will define the main characteristics of the accelerometer, namely sensitivity and noise.

3. Fabricated Devices

Microstructures (Fig. 2) were fabricated on the multi-project-wafer SOI micromachining process from MEMSCAP – SOIMUMPS [3]. These devices have different sets of parallel-plates for sensing and for actuation, symmetrically placed in each direction. The main design parameters are presented in Table 1.
4. Results

Firstly, the mechanical structure was studied using the Polytec’s micro system analyzer MSA-500 and the frequency response was obtained (Fig. 3). A resonance frequency of 515 Hz (expected 582 Hz) is retrieved from the phase plot while a quality factor $Q=0.7$ is found through transfer function curve fitting of the bode plot data.

Next, dynamic behavior experiments were performed. A readout circuit based on a charge amplifier was used to detect the capacitive changes while a data acquisition board (625 kHz sampling frequency) was used for the time measurement. The measured pull-in voltage was $2.931 \text{ V}$ (predicted value $\pm 2.916 \text{ V}$), while the simulated and measured nominal (0 g) pull-in time ($t_{\text{PI}}$) was 10.2 ms with $\alpha=1.01$ (Fig. 4a). The microstructure was also actuated with different step voltages $V_{\text{step}}$, in order to check the influence of the actuation voltage on the pull-in time (Fig. 4b). In both experiments very good agreement with the predicted results was achieved.

Finally, the device was tested using accelerations smaller than 10 mg (Fig. 5). These measurements were obtained using a setup comprising a platform with one fixed end and a free end controlled by a vibration exciter. The shaker changes the horizontal level (angle $\phi$) of the platform (where the sensor was placed) allowing the generation of accelerations below $300 \mu\text{g}$ ($a_{\text{ext}}=9.8\sin\phi$). The generated angle was calibrated using a very sensitive optical sensor (based on a fiber bragg sensor). A resolution of $0.25 \mu\text{s}/\mu\text{g}$ was measured along with a noise floor of $2.8\mu\text{g}/\text{Vs}$. 

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**Table 1. Accelerometer design parameters**

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Value</th>
<th>Device Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($m$)</td>
<td>0.249 mg</td>
<td>Damping coefficient ($b$)</td>
<td>$\text{gap} = \frac{2}{3}d_0$ $1.73 \text{ mNs/m}$</td>
</tr>
<tr>
<td>Mechanical spring ($k$)</td>
<td>3.33 N/m</td>
<td>Zero-displacement capacitance ($C_{\text{d0}}$)</td>
<td>2.53 pF</td>
</tr>
<tr>
<td>Zero-displacement gap ($d_0$)</td>
<td>2.25 $\mu$m</td>
<td>Mechanical-thermal noise</td>
<td>2.8$\mu$g/Hz</td>
</tr>
<tr>
<td>Natural resonance frequency ($f_0$)</td>
<td>582 Hz</td>
<td>Pull-in voltage ($V_{\text{PI}}$)</td>
<td>2.916 V</td>
</tr>
<tr>
<td>Zero-displacement actuation capacitance</td>
<td>0.66 pF</td>
<td></td>
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</tr>
</tbody>
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roughly 400 μg (110 μs). This was attributed to environmental disturbances since the total mechanical-thermal noise is expected to be below 40 μg (noise of 2.8 μg/√Hz and bandwidth of 180 Hz) and no measures were taken to isolate the experimental setup from building vibrations.

Fig. 4. a) Simulated and experimental results for a) nominal (0 g) pull-in time and b) pull-in time values for different values of α (α=V_{ap}/V_p)

Fig. 5. Simulation and experimental results of pull-in time variation with external acceleration

5. Conclusions and Future Work

The results presented here validate the pull-in time accelerometer concept. Further experimental work needs to be performed in a more controlled environment (to reduce the environmental noise) in order to evaluate the low noise specifications of the accelerometer.

Future work also includes a detailed analysis of the noise sources in the system.

6. Acknowledgements

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