Closed-loop operated time-based accelerometer

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Abstract

A high-resolution, high dynamic range capacitive accelerometer based on pull-in time measurement is described in this paper. The high sensitivity of pull-in time can be used to implement high performance accelerometers, but non-linearity and low dynamic range compromise device performance. A closed-loop approach using an electrostatic actuation mechanism to control the duration of the pull-in time is presented, which addresses the low dynamic range problem. Capacitive parallel-plates structures were used and the preliminary experimental results of closed-loop operation under several acceleration values confirm the potential of this technique and the overall accelerometer concept. The results show an accelerometer with high sensitivity (better than 6 μV/μg) and improved linearity over a large dynamic range.

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1. Introduction

State-of-the-art capacitive accelerometers have already demonstrated sub-μg resolution [1, 2] using open-loop approaches and dedicated microfabrication processes to yield large proof masses. The total noise floor threshold is currently set at 230 ng/√Hz [1]. The best noise performance accelerometers reported in literature are open-loop operated, requiring readout circuits with very high resolution, low noise and good stability. Despite that fact, closed-loop operated devices can in principle deliver increased dynamic range, linearity and bandwidth.

The concept of a μg-resolution accelerometer based on time measurement has been presented in [3]. In this approach, microstructures are electrostatically actuated to pull-in. If the microstructures are critically damped or overdamped, and an actuation voltage slightly higher than the nominal pull-in voltage is used, the pull-in
displacement profile includes a metastable region, where the mass moves slowly, which is located at 1/3 of the initial gap. The overall pull-in time ($t_{PI}$) is very sensitive to external forces. Repeatedly bringing the structure to pull-in, while measuring the $t_{PI}$, 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 the low requirements on the capacitive sensing circuit. However, when actuating a microstructure to pull-in, the changes in $t_{PI}$ with external acceleration are highly non-linear. Hence the open-loop response has a very limited dynamic range. Closed-loop control can address this problem, by manipulating the actuation voltages as a function of the $t_{PI}$ being measured. In this work, a new operation procedure for closed-loop operation enabling improved linearity over a large dynamic range is presented. The suitability of this approach is experimentally validated using fabricated MEMS structures.

2. Linearization technique

A linearization technique for a time-based accelerometer has been introduced in [4]. When actuating the structure to pull-in in one direction, the simultaneous use of a different set of parallel-plates, generating forces on the opposite direction (Fig. 1), increases the pull-in time, compensating for accelerations in the direction of pull-in. This technique can compensate for large offset accelerations, yielding a large increase in dynamic range. In this work, rather than the $t_{PI}$ measurement per se, the counter-actuation voltage ($V_{ef}$ - electrostatic feedback) necessary to keep $t_{PI}$ constant at the nominal value is used as the transduction mechanism. The pull-in time accelerometer is therefore operated in closed-loop, yielding an increased dynamic range.

![Fig. 1. Closed-loop pull-in accelerometer operation setup](image)

3. Fabricated MEMS Structures

The MEMS structures (Fig. 2) used to experimentally validate the closed-loop approach were fabricated using the SOIMUMP micromachining process from MEMSCAP [5]. The microstructures are symmetric and comprise different sets of parallel-plates for sensing and for actuation on both sides. The proof mass is suspended on 4 bi-folded springs, and the parallel-plate capacitors have a 2.25 $\mu$m gap at rest (Table 1). The inertial mass displacement is limited by mechanical stoppers placed in each lateral direction.

![Fig. 2. Microscope picture of the evaluated microstructure with detail showing a folded spring and stoppers](image)
Table 1. Main modeled design parameters of the structures

| Design parameter                  | Value                      |
|-----------------------------------|----------------------------|
| Mass \( (m) \)                   | 0.249 mg                   |
| Spring coefficient \( (k) \)     | 3.31 N/m                   |
| Zero-displacement gap \( (d_0) \) | 2.25 \( \mu m \)           |
| Zero-displacement actuation capacitance | 0.662 pF              |
| Zero-displacement sensing capacitance \( (C_0) \) | 2.53 pF              |
| Damping coefficient \( (b) \)    | \( \text{gap}=d_0 \) 1.76 mNs/m |
|                                   | \( \text{gap}=(2/3)d_0 \) 2.88 mNs/m |

4. Experimental Procedure and Results

The proof mass displacement is detected capacitively using a readout circuit based on a charge amplifier, while a microcontroller (CC2530) performs the time measurement and actuation voltage switching. A data acquisition board NI-USB-6281 provides the actuation voltages. A shaker is used to change the horizontal level of a platform where the sensor is placed, allowing the generation of small accelerations. The microstructure is continuously driven to pull-in with a constant \( V_{\text{step}} \) slightly higher than the nominal pull-in voltage \( (V_{\text{step}}=\alpha V_{\text{PI}}, \alpha=1.01) \). The \( t_{\text{PI}} \) measurement data from the microcontroller is processed in Matlab, where the algorithm to control the counter-actuation voltage \( (V_{\text{ef}}) \) is implemented. \( V_{\text{ef}} \) is recalculated and updated to keep \( t_{\text{PI}} \) constant around the nominal pull-in time (10ms). Several 1 Hz accelerations were applied to the sensor over different acceleration offsets (Fig. 3). Figure 4 shows the \( V_{\text{ef}} \) required to maintain \( t_{\text{PI}} \) constant under accelerations up to 0.4g.

![Fig. 3](image-url)  
Fig. 3. Experimental pull-in time and \( V_{\text{ef}} \) results under (a) an AC acceleration of 2.2mgpp at 1 Hz, over a 115mg offset and (b) an AC acceleration of 56mgpp at 1 Hz, over a 111mg offset

![Fig. 4](image-url)  
Fig. 4. Results of electrostatic feedback voltages, necessary to keep \( t_{\text{PI}} \) constant, as a function of DC acceleration values applied
5. Conclusions and Future Work

Within the range of accelerations tested it was found that $t_{\text{PI}}$ can be compensated, i.e. extended up to its nominal value of 10 ms. This shows that linearization methods enable the use of high sensitivity pull-in time accelerometers to measure acceleration over a much larger dynamic range than in open-loop operation. This approach improves the linearity of the sensor over a large input range (Fig. 4) and the sensitivity can be further increased by decreasing the number of parallel-plates used for actuation. Table 2 presents the preliminary sensor characteristics.

| Device parameter                        | Value                        |
|-----------------------------------------|------------------------------|
| Natural resonance frequency            | 515 Hz                       |
| Sensor bandwidth (BW=1/2$t_{\text{PI}}$) | 50 Hz                        |
| Sensitivity                            | >6 μV/μg                     |
| Operation range                        | ± 0.4 g                      |
| Time measurement resolution            | 0.125μs(clk8MHz)             |
| Mechanical-thermal noise               | 2.8μg/√Hz(200Hz, 40μg)       |
| Step voltage ($V_{\text{step}}$)       | 2.900 V                      |

The pull-in time accelerometer concept enables very good resolutions since the transduction method uses time measurements. For instance, using a 8 MHz clock on the time counting mechanism translates to a time measurement resolution of 0.125 μs. The resolution of a time-based accelerometer is not limited, in principle, by the capacitive measurement resolution (as is the case of most state-of-the-art accelerometers), but by the mechanical-thermal noise of the MEMS structures. With this electrostatic feedback approach, however, the stability and bandwidth can be limited by the control algorithm. The control algorithm used in this work is very simple and needs to be improved, since it presents clear limitations for large AC accelerations.

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