Full-Range Stable Operation of Parallel-Plate Electrostatic Actuators

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Abstract: A method based on voltage drive of a parallel-plate electrostatic actuator is presented that circumvents the pull-in instability and thus allows stable operation over the full gap. Actual device measurements are presented that confirm both the simplicity and effectiveness of the proposed method. Operation is limited only by the position jitter due to the time delay introduced by the readout circuits. Measurements confirm flexible and stable operation up to a mechanical stopper positioned at 2 µm of the 2.25 µm wide gap with a 30 nm ripple.

Keywords: Nonlinear dynamics, electrostatic actuators, stable extended travel.

INTRODUCTION

Electrostatic parallel-plate actuation is limited to displacements up to 1/3 of the gap due to the pull-in effect [1,2]. This limits the use of electrostatic parallel-plate actuation in many applications. In order to overcome this limitation several techniques have been proposed: geometry leverage [3], series feedback capacitor [4], current drive methods [5,6] and closed-loop voltage control [7].

Stable displacement over the full available range has not been achieved with these approaches, except for the geometry leverage technique, which is limited by the higher voltage levels required and the larger dimensions. It is interesting to note that these studies overlooked the opportunities provided by the dynamics of the devices. A fundamental MEMS characteristic is the achievable dynamic displacement beyond the static pull-in limitation [8]. This phenomenon provides the means for a new closed-loop voltage control method. This voltage drive approach introduces a simple and effective way to achieve stable displacements beyond the static pull-in limitation. The concept has been demonstrated by both simulations and measurements on fabricated microstructures. Stable displacements along the full available gap are experimentally achieved, and the simplicity and effectiveness of the method are an added value to parallel-plate electrostatic actuators.

DYNAMIC VOLTAGE DRIVE: ON-OFF CLOSED-LOOP

The basic idea is the comparison of the momentary actuator displacement being measured with the fixed desired displacement. According to the comparison result, the applied voltage on the actuator is changed between two values (unlike traditional feedback): between a high level if the measured displacement is lower than the reference one, and a lower level, if the actuator displacement is higher than the reference value.

The concept is simple and similar to the on-off method used in linear control theory. A block diagram of the proposed method is shown in Fig. 1. The method relies on the dynamics of the MEMS devices, namely the shift between stable and unstable trajectories (shift on the basin of attraction) by changing the applied voltage. This implies that the device must be overdamped or critically damped. In underdamped devices the inertial forces are not significantly counteracted by damping forces and the oscillatory regime typical of these devices compromises the method.

Time Delays in the Feedback Loop

During switching the structure continues the movement and consequently an extra displacement results, leading to a small ripple around the desired displacement. This effect is aggravated by any time delay introduced by the circuits.

Using a large-signal model implemented in Simulink [8,9] for a 1-DOF actuator with the characteristics shown in Table 1 the proposed control method was verified through simulations. The equivalent mechanical and estimated electrical noise sources are included in the model, and a time delay is introduced in the feedback loop. The introduced
delay includes both the switching times and the circuit delays. Fig. 2 shows the simulated performance of the control loop for a delay of 15 µs. The reference displacement is set at 1.5 µm and the voltage levels are defined as: \( V_{\text{high}} = 4V \) and \( V_{\text{low}} = 2V \). The simulated MEMS actuator has a theoretical static pull-in voltage at \( V_{\text{pi}} = 3.820V \) and the stoppers are placed at 2 µm in a 2.25 µm gap.

### Table 1. Microdevice parameters

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (m)</td>
<td>4.27 µg</td>
<td></td>
</tr>
<tr>
<td>Mechanical spring (k)</td>
<td>1.29 N/m</td>
<td></td>
</tr>
<tr>
<td>Resonance frequency ( (f_0) )</td>
<td>2.77 kHz</td>
<td></td>
</tr>
<tr>
<td>Initial gap distance ( (d_0) )</td>
<td>2.25 µm</td>
<td></td>
</tr>
<tr>
<td>( C_{00} ) (initial zero-displacement actuation capacitor)</td>
<td>141 fF</td>
<td></td>
</tr>
<tr>
<td>Damper width ( (w) )</td>
<td>10.6 µm</td>
<td></td>
</tr>
<tr>
<td>Damper length ( (l) )</td>
<td>282 µm</td>
<td></td>
</tr>
<tr>
<td>Total nr. of arms</td>
<td>72</td>
<td></td>
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</tbody>
</table>

Additional simulations were performed using different delay times with the results shown in Fig. 3. As predicted, the ripple depends on the delay times and the larger is the delay, the longer is the displacement beyond the reference displacement value. Despite its simplicity, these results predict the feasibility of the on-off control method. The main constrains are the ripple in the microstructure position around the set value due to time delays in the readout circuits. According to simulations, the control remains effective for delays as large as 30 µs. Since switching time in a comparator is lower than 1 µs, the bottleneck for actual implementation is the phase characteristics of the readout circuit.

**EXPERIMENTAL RESULTS**

A device fabricated in the Bosch epi-poly process [10] was used to verify the method (Fig. 4). The fabricated structure is composed of four folded beams, 340 µm long and 2.5 µm wide, connected to two rigid central bars of about 1mm. Parallel-plate capacitors with a 2.25 µm gap are used for actuation. The displacement measurement involves sensing the changes of various sets of differential capacitors. The measured pull-in for the structure used is at 3.34V. The mechanical stoppers limit the actuator displacements to 2 µm in a 2.25 µm gap.

Since the readout electronic circuit is a critical component for the implementation of the closed-loop on-off control, the readout circuit used for differential capacitance measurement is introduced here. A differential output circuit [11, 12] have been used to measure the displacement on the fabricated MEMS actuators. The fabricated MEMS devices have differential sensing capacitors and allow for capacitive displacement detection.

A differential sense interface is used with the sensing stationary electrodes connected to the differential input of the charge amplifier and the drive signal applied to the common movable central point. A schematic of the differential output circuit is shown in Fig. 5. The circuit is composed of three main blocks: a buffer amplifier, two charge amplifiers and an AM-demodulator. The buffer amplifier sets the gain for the carrier input voltage, the charge amplifier modulates the amplitude of the carrier signal proportional to the capacitance changes and the demodulator shifts the modulated carrier signal to the (mechanical) baseband.

The differential sensing circuit depicted in Fig. 5 was implemented at the PCB level. Commercially available trans-conductance amplifiers [13] were used in the high-frequency path. The AM-demodulator stage was implemented using a 1496 Motorola demodulator. The bandwidth of the low-pass filter was set at 200 kHz, resulting in total estimated circuit time delay at 5 µs.
Operation of the on-off method has been experimentally verified using structures hermetically sealed and filled with neon at $0.6 \times 10^5$ Pa by the manufacturer. A comparator was introduced in the readout circuit to close the feedback loop (see dashed components in Fig. 5). The voltage $V_D$, which is proportional to the actuator displacement, is compared with the reference value, $V_{\text{Ref}}$, and the drive feedback signal varies between $V_H$ and $V_L$ according to the comparator output. $V_H$ and $V_L$ are set by:

$$V_H = \frac{R_S}{R_S + R_H}V_+ \quad \text{and} \quad V_L = \frac{R_S//R_L}{(R_S//R_L) + R_H}V_+$$  \(1\)

The mechanical stoppers limit the actuator displacements to $2 \mu m$ in a $2.25 \mu m$ gap. The readout output voltage, $V_D$, ranges from 0 (zero displacement) until $2.2 V$ ($2 \mu m$ displacement) and at 1/3 of the gap ($0.75 \mu m$) the output readout voltage is 0.62 V. First, the operational details of the method were verified by measuring the comparator output and actuator displacement at the time the feedback loop is closed. Measured results are shown in Fig. 6.

Stable positioning at a voltage selected operated point beyond the static pull-in limitation is achieved in agreement with simulations. Additional measurements were performed to check the stability of the method over time and at different reference positions. Stable operation over the full available gap ($2 \mu m$) is observed. The results for three different points are shown in Fig. 7.

![Fig. 5. Schematic of the differential sense interface](image)

![Fig. 6. Measured operational details of the proposed technique.](image)

![Fig. 7. Measured voltage-drive stable operation beyond the theoretical pull-in limitation.](image)

Although the stoppers limit operation up to 89% of gap, full range operation can be achieved with this approach on devices without mechanical limitations. At very small gaps, the damping forces are huge due to the very narrow channel. These damping forces slow even further the structure displacements, improving the dynamic device response when operated with the on-off method. The high damping coefficient at very small gaps is in fact expected to enhance operation.

![Fig. 8. Measured changes in ripple amplitude with different voltage levels.](image)
Finally, the voltage levels were dynamically adjusted to check the influence on the ripple. Results for the case of a reference voltage, \( V_{\text{Ref}} = 1.38 \text{ V} \) are shown in Fig. 8. The figure clearly shows that the voltage levels are not critical for device operation, but adaptation during positioning does reduce the ripple (= position uncertainty) of the on-off control. The best results obtained so far using the most suitable voltage level combination available yield a ripple of about 30 mV (\( \cong 30 \text{ nm} \)). The main source of ripple is the time delay introduced by the readout. The microactuator used has a mechanical-thermal noise (theoretical) of \( \cong 56 \text{ pm} \), while the predicted readout noise referred to the input is about \( \cong 180 \text{ pm} \). For ideal time delay the stability of the on-off approach would be limited by noise, and for the device used the stability would be \( \cong 230 \text{ pm} \), which is equivalent to the ripple caused by a delay time of about 50 ns. Therefore, the stability of the position is set by the mechanical-thermal noise and the readout noise, for a time delay around or below 50 ns only.

**CONCLUSIONS**

A novel technique to extend the travel range of electrostatic actuators is presented. The simplicity of the approach is an added value to parallel-plate based electrostatic actuator systems. Although the stoppers limit operation up to 89% of gap, full range operation can be achieved with this approach on devices without mechanical limitations. Table 2 makes a small comparison of this method with methods previously reported in literature.

The voltage drive relies on the device dynamics and the dependence of the positioning ripple on the time delay introduced by the readout. Limitations are the need for displacement sensing and the fact that it can be used in low-Q devices only. In the present system a ripple as small as 30 nm (over the full gap available) has been achieved.

<table>
<thead>
<tr>
<th>Method</th>
<th>Maximum displacement</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Geometry leverage [3]</td>
<td>( \cong 90% )</td>
<td>• Simple</td>
<td>• Increased actuation voltage ( \cong ) Increased device area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Does not require a sensing mechanism</td>
<td></td>
</tr>
<tr>
<td>Series capacitance [4]</td>
<td>( \cong 65% )</td>
<td>• Simple</td>
<td>• Reduce travel due to parasitic capacitances and residual charge ( \cong ) Increased actuation voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Does not require a sensing mechanism</td>
<td></td>
</tr>
<tr>
<td>Current drive [5]</td>
<td>( \cong 65% )</td>
<td>• No increase in device area</td>
<td>• Charge pull-in due to parasitic capacitances and tip-in instability ( \cong ) On-board current sources and charge control circuitry ( \cong ) Increased actuation voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Does not require a sensing mechanism</td>
<td></td>
</tr>
<tr>
<td>Feedback Linearization [7]</td>
<td>74%</td>
<td>• Does not require increased actuation voltage</td>
<td>• Complex ( \cong ) Difficult implementation ( \cong ) Sensing mechanism needed</td>
</tr>
<tr>
<td>This paper</td>
<td>89%</td>
<td>• Simple</td>
<td>• Ripple (due to delay) ( \cong ) Sensing mechanism needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Flexible ( \cong ) 100% travel range if used without stoppers</td>
<td></td>
</tr>
</tbody>
</table>

**REFERENCES**