CASE STUDY:
A Capacitive Accelerometer

Joel Voldman
Massachusetts Institute of Technology
Thanks to SDS and Tim Dennison (ADI)
Outline

> Accelerometer fundamentals

> Analog Devices accelerometer
  • History
  • Structure
  • Design and modeling
  • Fabrication and packaging
  • Noise and accuracy
Measurement choices

> Two approaches to measuring acceleration
  - Open loop: Measure change due to acceleration
  - Closed loop: A disturbance in a position control system
Accelerometer types

> Open vs. closed loop sensing
  • Open loop: Measure change due to acceleration
  • Closed loop: A disturbance in a position control system

> Quasi-static vs. resonant sensing
  • Quasi-static sensing
    » Mechanical resonant frequency > Frequency of acceleration
    » Measure displacement due to acceleration
      Optical, Capacitive, Piezoresistive, Tunneling
  • Resonant sensing
    » Measure change in resonant frequency
      Due to position-dependent nonlinear spring

> Today’s example involves a quasi-static accelerometer
Accelerometer fundamentals

> Displacement and acceleration are coupled together by a fundamental scaling law

  • A higher resonant frequency implies less displacement
    » high $f$ & low sensitivity
  • Measuring small accelerations requires floppier structures
    » high sensitivity and low $f$

> Johnson noise in the damping mechanism gives rise to a fundamental noise floor for acceleration measurement

\[ x = \frac{F}{k} = \frac{ma}{k} \]
\[ x = \frac{a}{\omega_0^2} \]
\[ a_{n,rms} = \sqrt{\frac{4k_B T \omega_0}{mQ}} \]
Accelerometer specifications

- Initial application arena was automotive crash sensor
- Navigation sensors have tighter specs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Automotive</th>
<th>Navigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>±50g (airbag) ±2g (vehicle stability system)</td>
<td>±1g</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>DC- 400Hz</td>
<td>DC-100Hz</td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt;100mg (airbag) &lt;10mg (vehicle stability system)</td>
<td>&lt;4μg</td>
</tr>
<tr>
<td>Off-axis Sensitivity</td>
<td>&lt;5%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>&lt;2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Max. Shock in 1msec</td>
<td>&gt;2000g</td>
<td>&gt;10g</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40°C to 85°C</td>
<td>-40°C to 80°C</td>
</tr>
<tr>
<td>TC of Offset</td>
<td>&lt;60mg/°C</td>
<td>&lt;50 μg/°C</td>
</tr>
<tr>
<td>TC of Sensitivity</td>
<td>&lt; 900ppm/°C</td>
<td>±50ppm/°C</td>
</tr>
</tbody>
</table>

Piezoresistive accelerometers

- Use piezoresistors to convert stress in suspension beam → change in resistance → change in voltage

- First MEMS accelerometer used piezoresistors
  - Roylance and Angell, IEEE-TED ED26:1911, 1979
  - Bulk micromachined
  - Glass capping wafers to damp and stop motion

- Simple electronics

- Piezoresistors generally less sensitive than capacitive detection


Capacitors for position measurement

> Single capacitors
  - Capacitance is function of gap or area
  - Can be nonlinear

> Differential capacitors
  - One capacitor increases while the other decreases

---

Image by MIT OpenCourseWare.

Image by MIT OpenCourseWare.

Cite as: Joel Voldman, course materials for 6.777J / 2.372J Design and Fabrication of Microelectromechanical Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

Using a differential capacitor

> Differential drive creates sense signal proportional to capacitance difference
> Gives zero output for zero change
> Output linear with gap

\[ V_0 = -V_S + \frac{C_1}{C_1 + C_2} (2V_S) = \frac{C_1 - C_2}{C_1 + C_2} V_S \]

for parallel-plate capacitors where only \( g \) changes, this becomes

\[ V_0 = \frac{g_2 - g_1}{g_1 + g_2} V_S \]

Image by MIT OpenCourseWare.
### Bulk-micromachined capacitive accelerometer

> Fabrication not reported, but likely uses nested-mask process

<table>
<thead>
<tr>
<th>Step</th>
<th>Image Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. First silicon etching</td>
<td><img src="image1" alt="First silicon etching" /></td>
</tr>
<tr>
<td>B. Second silicon etching</td>
<td><img src="image2" alt="Second silicon etching" /></td>
</tr>
<tr>
<td>C. Third silicon etching</td>
<td><img src="image3" alt="Third silicon etching" /></td>
</tr>
</tbody>
</table>


Cite as: Joel Voldman, course materials for 6.777J / 2.372J Design and Fabrication of Microelectromechanical Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].
Thermal accelerometer

> MEMSIC thermal convection accelerometer

> Gas is proof mass

> Movement of gas under acceleration changes thermal profile
Transimpedance circuits

> The simplest type of circuit measures the displacement current in a capacitor using a transimpedance amplifier
  
  - Transimpedance converts current to voltage
  - Nulls out parasitic capacitance

> If source is DC, measure velocity of motion

> Velocity is not really what we want…

\[ Q = C(x, t)V_c \]

\[ v_+ \approx v_- = 0 \Rightarrow V_c = V_s \]

\[ i_C = \frac{dQ}{dt} = C(x, t) \frac{dV_s}{dt} + V_S \frac{\partial C}{\partial x} \bigg|_{V_S} \frac{dx}{dt} \]

\[ i_C = V_S \frac{\partial C}{\partial x} \bigg|_{V_S} \frac{dx}{dt} = -\frac{V_0}{R_F} \]

\[ V_0 = -R_F V_S \frac{\partial C}{\partial x} \bigg|_{V_S} \frac{dx}{dt} \]

constant

Image by MIT OpenCourseWare.
Adapted from Figure 19.6 in Senturia, Stephen D. *Microsystem Design.*
Transimpedance circuits

> If source is AC, can measure position

> First, must use frequency high enough such that velocity term is negligible

> Second, operate above corner frequency of LP filter

\[
i_C = \frac{dQ}{dt} = C(x,t) \frac{dV_c}{dt} + V_c \frac{\partial C}{\partial x} \left|_{V_c} \right. \frac{dx}{dt}
\]

\[
V_s = V_{s0} \cos(\omega t) = \text{Re}\{V_{s0} e^{j\omega t}\}
\]

\[
i_C = \left[ C(x,t) j\omega + \frac{\partial C}{\partial x} \left|_{V_c} \right. \right] \frac{dx}{dt} V_s
\]

\[
i_C \approx C(x,t) j\omega V_s
\]

\[
V_0 = -i_c \left( C_F // R_F \right) = -i_c \frac{R_F}{1 + j\omega C_F R_F}
\]

\[
V_0 \approx -\frac{i_c R_F}{j\omega C_F R_F} = -\frac{-i_c}{j\omega C_F} \approx -\frac{C(x,t) j\omega V_s}{j\omega C_F}
\]

\[
V_0 \approx -\frac{C(x,t)}{C_F} V_s
\]
Non-inverting op-amp circuits

Now there is no virtual ground and parasitic capacitance appears in output

\[ V_0 = V_x = \frac{C_1 - C_2}{C_1 + C_2 + C_P} V_S \]
AC Methods Require Demodulation

> For AC methods, output signal is a HF sinusoid (carrier) multiplied by a LF signal

> This is an amplitude-modulated (AM) signal

> We want to retrieve the low-frequency component

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_S(t) \]

Image by MIT OpenCourseWare.

Synchronous Demodulation

> Use a nonlinear circuit to multiply $V_0$ by an in-phase sinusoid
> This demodulates to baseband
> Relative phase is important

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_S \]

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_{s0} \cos(\omega t) \]

\[ V_d = V_0 \cdot V_s = V_0 \cdot V_{s0} \cos(\omega t + \theta) \]

Allow phase shift

\[ V_{out} = -\frac{C(x,t)}{2C_F} V_{s0}^2 \cos(\theta) \]

\[ V_d = -\frac{C(x,t)}{2C_F} V_{s0}^2 \left[ \cos(\theta) + \cos(2\omega t + \theta) \right] \]

Signal-to-noise Issues

> To get a big signal, use a big voltage

— BUT —

Voltage creates a force that can modify the state of the mechanical system (analogous to the self-heating problem in resistance measurement)

> Noise floor *minimum* often set by LPF bandwidth

> But amplifier noise will often dominate

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_S(t) \]
Analog Devices accelerometer

> **Genesis:** An ADI engineer heard about forming mechanical sensors on silicon

> **Market pull was airbag accelerometers (50g)**
  - Current product was $50
  - Auto manufacturers wanted $5 price point

> **Team was formed in 1986, first product in 1993**
  - Fabrication process was under development since early 80’s at Berkeley
Analog Devices accelerometer

> Initially partitioned system to *integrate* electronics on-chip
  - This ensured that they could achieve good SNR

> BUT
  - Entailed large infrastructure costs that essentially hemmed future opportunities

> This is an example where up-front system partitioning has *multi-decade* consequences
ADI system partitioning

> How to integrate MEMS + circuits?

> Circuits typically are run on continually changing (and improving) fabrication lines

> MEMS typically cannot economically support such high throughputs

> Foundries will not accept non-pristine wafers

> Thus, must combine both in-house in a dedicated foundry
  • This usually sets circuit technology
  • For ADI, foundry is in Cambridge and Limerick
ADI system partitioning

> How to integrate MEMS + circuits?

> Several different approaches

  • MEMS first
  • Circuits first
  • MEMS in the middle

> ADI chose MEMS-in-the-middle

  • Mostly developed at Berkeley
  • 6” fab line
  • ~1 million sensors/week (as of 2005)
Analog Devices ADXL50

Courtesy of Analog Devices, Inc. Used with permission.
Differential capacitor structure

Closer views

Even closer

Fabrication sequence

Image by MIT OpenCourseWare.


Cite as: Joel Voldman, course materials for 6.777J / 2.372J Design and Fabrication of Microelectromechanical Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].
Packaging

> When to do die saw, before or after release?

> ADI decided to do die separation after release and invented a wafer-handling method to protect the released region during sawing

  • One tape layer with holes corresponding to mechanical region
  • A second tape layer covering the entire chip
  • Saw from the back (must have pre-positioned alignment marks on wafer back to do this)
Packaging

> Processing issues
  • Stiction at- and post-release
    » Solved at-release stiction with bumps under poly structures
    » Post-release stiction avoided with proprietary coating
      Thermally evaporated silicone coating
      Has to withstand packaging temps

> Laser trimming
  • Set offsets, slopes, etc.
  • At wafer scale
  • Before packaging...
System diagram

> Oscillator provides AC waveform for sensing

> Waveforms:

Stiffness of springs

> Parallel-plate approximation to sense capacitance is off by about 50%

> Beam bending model gives good estimate of stiffness

\[
k \approx 2 \frac{\pi^4}{6} \left[ \frac{EWH^3}{(2L_1)^3 + (2L_2)^3} \right] \approx 5.6 \text{ N/m}
\]

\[
\omega_0 = 24.7 \text{ kHz}
\]

\[
C_{\text{sense}} \approx 42 \frac{\varepsilon_0 HL_0}{g_0 \pm y} \approx 60fF \left[ 1 \pm \frac{y}{g_0} \right]
\]

Design and modeling

> Q of mechanical resonance is 5
  • Extremely hard to model accurately
  • Squeezed film damping between fingers
  • Couette drag beneath proof mass
  • Complex actual geometry
  • Rough model gives Q = 34, a poor estimate
First accelerometer used feedback control to keep plates fixed

Let’s use PD control to see what it affects \( K(s) = K_0(1 + \gamma s) \)

Input is disturbance \( D(s) \) – acceleration

Output is force from controller \( F(s) \)

\( H(s) \) is accelerometer: SMD

\[
\frac{F(s)}{D(s)} = -\frac{HK}{1 + HK} = -\frac{K_0}{m} \left(1 + \gamma s \right)
\]

\[
s^2 + \left( \frac{b}{m} + \frac{\gamma K_0}{m} \right) s + \frac{k + K_0}{m}
\]
> Use feedback to get both
  • Critical damping (when ON)
  • Insensitivity to material properties

> Choose $K_0 \gg k$
  • ADI chose 10x

> Critical damping is when $b^2 = 4ac$ ($Q_{\text{closed-loop}} = 1/2$)
  • Can pick $K_0$ and $\gamma$ to meet both requirements

> Sensor response will be insensitive to changes in $k$

\[
F(s) = -\frac{K_0}{m} (1 + \gamma s)
\]
\[
D(s) = s^2 + \left(\frac{b}{m} + \gamma \frac{K_0}{m}\right) s + \frac{k + K_0}{m}
\]
\[
\left(\frac{b}{m} + \gamma \frac{K_0}{m}\right)^2 = 4 \left(\frac{k + K_0}{m}\right)
\]
\[
\left(\frac{b}{m} + \gamma \frac{K_0}{m}\right) \approx 2 \sqrt{\frac{K_0}{m}}
\]
\[
\left(\frac{\omega_0}{Q_{\text{o.l.}}} + \gamma \frac{K_0}{m}\right) \approx 2 \sqrt{\frac{K_0}{m}}
\]
\[
\gamma \frac{K_0}{m} \approx 2 \sqrt{\frac{K_0}{m}} - \frac{1}{Q_{\text{o.l.}}} \sqrt{\frac{k}{m}} \approx 2 \sqrt{\frac{K_0}{m}}
\]
\[
\gamma \approx 2 \sqrt{\frac{m}{K_0}}
\]
The next generations

> In the next generation, ADI abandoned feedback

> Why?

• After years of testing, ADI found that polySi was structurally stable for intended markets
• Feedback required extra electronics $\rightarrow$ bigger chip $\rightarrow$ $$
• Needed external capacitor to set LPF
  » Extra cost, extra complexity
• Closed-loop design was not ratiometric to power supply
  » Customers needed to measure supply voltage
• DC bias at fingers for force feedback caused charges to move and thus devices to drift

> Therefore, they removed feedback
Next generation specifications

> Text study is of ADXL150 (XL76)

> Text lists 22 specifications, covering sensitivity, range, temperature range, supply voltage, nonlinearity, cross-axis response, bandwidth, clock noise, drop test, shock survival, etc etc.

> Also, response is ratiometric, proportional to the supply voltage

> Sensitivity is $\beta V_s = 38 \text{ mV/g}$

$$V_{out} = \frac{V_s}{2} \pm \alpha + a \beta V_s$$

Image removed due to copyright restrictions.
Noise and accuracy

> Noise is specified as 1 mg/Hz$^{1/2}$ in a bandwidth from 10 Hz to 1000 Hz

> Corresponding Brownian noise estimate is half that value, corresponding to a rms position noise of 0.013 nm

> Offset errors
  - If device is not perfectly balanced at zero g, turning on voltage aggravates the offset
  - Accurate etching required special “dummy” features to ensure that all cuts had the same profile (we have seen similar effects when we looked at DRIE)

> Cross-axis sensitivity is low because of squeeze-film damping and differential capacitor measurement
ADXL202 2-axis accelerometer

Then moved from two 1-axis sensors to one 2-axis
Newer designs

> ADXL203 two-axis accelerometer

> Supports are in center of die to cancel 1st-order stresses due to packaging
The latest design: ADXL40

> The newest designs use an SOI-MEMS process
  > Also developed at Berkeley

> Enables several circuit features
  > 0.6 μm CMOS allows 10x more transistors in same size
  > Allows poly fuse trims to be set on-chip
    » Can trim AFTER packaging

![Diagram](https://example.com/diagram.png)

The latest design: ADXL40

> MEMS

• Higher-aspect ratio structures lead to more squeezed-film damping \( \Rightarrow Q=1 \)

• Trench isolation allows self-test to be electrically isolated from sensing fingers

  » Allows 2x voltage applied \( \Rightarrow 4x \) force
ADXL40

> Die shots

Image removed due to copyright restrictions.
Summary

> Accelerometers are a MEMS success story

> Early system partitioning decisions have had profound downstream effects
  • Eases sensor design and sensing
  • Requires large internal infrastructure
    » And can never go to TSMC…