Design and Development of Accelerometers and Gyros

Tutorial 2B
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Presentation Outline

- Inertial Sensor Design Approach
- Product Improvements
- Applications
- Gyroscope Design & Applications
- Conclusions
Acceleration can be measured using a simple mass/spring system.

- Force = Mass * Acceleration
- Force = Displacement * Spring Constant
- So, Displacement = Mass * Acceleration / Spring Constant
Sensor Principle: Differential Capacitive Sensing

- Use Silicon to make the spring and mass, and add fingers to make a variable differential capacitor.
- Measure change in displacement by measuring change in differential capacitance.

Sensor at rest:
- Mass
- Spring
- Fixed outer plates
- Anchor to substrate

Responding to an applied acceleration (movement shown is greatly exaggerated):
- Applied acceleration
- CS1 < CS2
ADI Accelerometers: Key Dimensions
Interesting Facts

- 0.1 pF per side for the differential capacitor
- 20 zF (10^-21 F) smallest detectable capacitance change
- 2.5 pm minimum detectable beam deflection (one tenth of an atomic diameter)

Proof Mass = 0.7 µgram

125 Micron Overlap
1.3 Micron Gap
3 Microns Thick
iMEMS® Technology
Capacitance to Voltage Conversion

MOVABLE BEAM
ACCELERATION
UNIT CELL

CLOCK A
AMP
CLOCK B

RECTIFIED VOLTAGE OUTPUT
SYNCHRONOUS DEMODULATOR
Design Evolution
ADXL50 (1993)

- Circuit architecture
  - Closed loop
    - Concerns about polysilicon lead to force feedback design
  - 0.6 V p-p complimentary modulation of differential capacitors
  - Resistive biasing/FB (3 MΩ)

- MEMS design
  - Dielectric under structure
  - Anchors at periphery
  - Beam not centered or symmetric
Design Evolution
ADXL76 (1996)

- **Circuit architecture**
  - Open loop
    - Polysilicon robustness now confirmed
    - Full supply complimentary clocks
    - Reduced die size
    - Ratiometric
  - Switched cap filter
  - Switch biasing

- **MEMS Design**
  - Conductor under structure
  - Anchors on axis
  - Beam centered & symmetric
    - Better offsets & tempco’s
Design Evolution
ADXL78 (2002)

- Circuit architecture
  - Closed loop
    - Overload performance pushed design back to feedback
    - Servo complimentary clock amplitude
    - Differential architecture
      - Ratiometric & EMI resistant

- MEMS Design
  - Two structures
  - Conductor under structure
  - Two springs/structure
    - Robust to process variations
  - Beam centered & symmetric

- Layout
  - Compact!
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Die Area</td>
<td>10.8</td>
<td>5.4</td>
<td>2.7</td>
<td>2.5</td>
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<td>MEMS Area</td>
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<td>0.38</td>
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<td>% MEMS</td>
<td>4.0%</td>
<td>7.0%</td>
<td>10%</td>
<td>8.8%</td>
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<tr>
<td>(C_s)</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>160</td>
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<tr>
<td>(f_o)</td>
<td>25.0</td>
<td>24.5</td>
<td>24.5</td>
<td>12.5</td>
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<tr>
<td>Offset</td>
<td>3.0</td>
<td>1.0</td>
<td>0.5</td>
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</tr>
</tbody>
</table>

MEMS Area: mm², % MEMS, \(C_s\): fF, \(f_o\): kHz, Noise: mgee/rt.hz, Offset: gee
**Design Example:**
**ADXL203 50 mg accurate, +/- 1.7 g, 2 axis XL**

- **Problem:**
  - How do we get a 10x improvement in null accuracy with minimal investment?

- **Solution:**
  - Start with ADXL202 platform and make minimal changes
    - Structure
    - Electronics
Design Example: ADXL203 50 mg accurate, +/- 1.7 g, 2 axis XL

🌟 Problem:
- How do we get a 10x improvement in null accuracy with minimal investment?

🌟 Solution:
- Start with ADXL202 platform and make minimal changes
  - Structure
  - Electronics
Move anchors towards center of die

- Modeling & experiment verification

- Lower resonant frequency (10 kHz -> 5.5 kHz)

- Use 4 μm polysilicon
ADXL203 Highlights

- Culmination of 15 years of learning
  - Process, structure design, electronics, and packaging
- Typical 50 mg absolute accuracy over temperature, -40 to 125°C
  - Measure absolute tilt to 3 degrees over temp
  - Resolve tilt changes to 0.01 degrees (1 mm over 100 m)
- Minimalist circuitry
  - For small size, thus low cost
  - Low noise (110 µg/rt Hz.)
  - Low drift
- Small 5 x 5 x 2 mm LCC package enabled by integration

Details:
- Sensitivity
  - 8.2 nm/g
- Resolution
  - 1 Hz BW -> 800 fm (Gyro 16 fm)
  - 100 fF -> 50 zF (Gyro 12 zF)
- Offset
  - 0.05 g -> 4 Å (250 ppm)
ADXL203 0 g Data Over Temperature

Zero g vs. Temperature
XL203 Characterization
Lot 74990 Group B

Volts @1V/g

-50  -40  -30  -20  -10   0   10   20   30   40   50   60   70   80   90   100   110   120   130

2.4  2.42  2.44  2.46  2.48  2.5  2.52  2.54  2.56  2.58  2.6

Temp C (part going hot first, then cold)
5 degrees per minute going down, 10 degrees per minute going up

+ 50 mg

- 50 mg
Interesting Applications

- Air Bags
- Gesture Recognition
- Security
- Tilt Correction
- GPS Inertial Ref
- Toys – Sports
- Vibration Sense
- Projector Keystone
“There are 1.6 MEMS devices per person in use today in the U.S. and the number is expected to grow to nearly 5 devices per person by 2004.

—MEMS Industry Group
ADI’s iMEMS® Inertial Sensors in Automotive Systems

- Air Bag Systems
- Navigation Systems
- Car Alarms
- Vehicle Dynamic Control Systems
- Rollover Safety Systems
ADI Sensors Used in Consumer and Industrial Products and Applications

- Health Products (Blood Pressure Monitors)
- Performance Meters
- Sports Aids
- Sports Products (Pedometers)
- PC Security
- LCD Projectors
Blood Pressure Monitor

- **Company:** OMRON
- **Product:** Portable Blood Pressure Monitoring Device
- **ADI Inside:** ADXL311JE
- **Function:** Tilt Sensing

- Measures forearm angle to ensure correct positioning of the wrist (at heart level)
- Results in higher blood pressure measurement accuracy
Developing Applications
Motion Sensing in Smart Handhelds

- Tilt-sensing and motion recognition for handheld devices
- Intuitive spatial browsing on small screen devices
- Orientation and location detection for mobile phones
**Situational Awareness**

- Enables optimization of phone features and functions based on the detection of environmental context, e.g.:
  - Turns off display when phone is held at ear level
  - Turns off vibrating mode when phone is not carried or held (not moving)
  - Automatically activates pedometer function when walking motion is recognized
  - Automatically selects portrait or landscape display orientation for picture taking or gaming
  - Manages incoming calls based on user’s activity level
iMEMS® Technology For Handhelds

- Large Document Panning and Zooming
  - Enables intuitive display control of large documents (e.g. maps) through tilt or inertial sensing

- Single-Handed Operation
  - Enables one hand operation of simple functions

- Data Entry/Selection
  - Enables menu and cursor control through tilt sensing and motion detection

- Intuitive Gaming
  - Enhances gaming experience by providing intuitive, button-less control of gaming action

- Electronic Compass Tilt-Compensation
Cellular Phone/Pedometer

- **Company:** FUJITSU
- **Product:** DoCoMo Cellular Phone for Japanese Market
- **ADI Inside:** ADXL311JE
- **Function:** Motion Sensing for Pedometer Function

- Displays number of steps walked
- Displays distance walked based on stride input
- Displays calories expanded based on user weight input
Pedometers

Pedometer model SDM [ Tailwind and SDM Triax 100
Company: Nike, Inc.
ADI Inside: iMEMS® ADXL78 and ADXL278 accelerometers

Function: Shock, tilt and inertial sensing for foot motion measurements resulting in accurate speed and distance information
Laptop Security

Anti-Theft™ PCMCIA Card for Laptop Computers
Company: Caveo Technology
ADI Inside: iMEMS® ADXL202E accelerometer

Function: Inertial and tilt measurement for security perimeter and motion password setting
Gaming

Game Boy® Advance with Kirby Tilt-n-Tumble™ and Happy Panechu™
Company: Nintendo
ADI Inside: iMEMS® ADXL202 and ADXL202E accelerometers

Function: Tilt measurement resulting in intuitive game feature control
MEMS in Personal Communications

Future Potential Uses of MEMS

- Antennas
- Color bi-stable display
- Micro-switches
- Tunable capacitors and inductors
- Tunable filters
- Directional microphone
• Automotive HVAC Controls

• Humidistat and motor speed controls

• Time Controls

• Heat alarms

Source: Zigbee
Wireless Buildings

Key to success: reduced installation costs

Source: Zigbee
Integrated Micromachined Gyro

Single Chip Rate Sensor
5V Operation
Std Atmosphere
150 deg per second
Self-Test
0.03 deg/sec/sqrt hz
Compensated 5%

Lessons Learned In Accelerometer Development of Meso Structures Detecting Nano dimensions now applied to sub pico-dimensions
iMEMS Gyro Sensor

- Coriolis movement sense fingers
- Rotation sense Direction
- Drive direction
- Resonator drive fingers
- Coriolis effect movement direction
Coriolis Accel Full Scale Deflection 0.3 Nanometers
Quadrature Rejection 1 ppm

Design Issues:
Aerodynamics, Shock, Vibration, Thermal
Simplified Gyro Blockdiagram

- Synchronous Demodulation and Rectification of Y Axis Signal
- Drive and Feedback Loop
- Rateout
- Low pass filter & Amplifier
Gyro Packaging: in Vacuum or Air?

High Q

Low Q

Complicated electronics

Less complicated electronics

Phase Jitter

Very critical

Less critical
Gyro Structure

* Separated Accelerometer and Resonator
Electronic Design and Mechanical Design Interdependent

Functional Block Diagram
Gyro - Root Allan Variance

\[ \sigma(t) = \frac{1}{2(m-1)} \sum_{i=1}^{m-1} (y(i+1) - y(i))^2 \] for \( i \) averaged over \( \tau \).
Automotive Gyroscope Markets

- **Vehicle Dynamic Control**
  - Interaction between anti-lock brake, electronic brakeforce distribution, traction control, and active yaw control systems to achieve dynamic stability

- **Rollover**
  - Extension of airbag safety systems for SUVs, vans, pickup trucks, and high-end vehicles

- **Navigation**
  - Provide additional real-time location input and directions when GPS satellites are not available.
Applications for Gyroscopes

- **Flight Controls/Training Systems**
  - Unmanned aircrafts
  - Supplement to flight dynamic control
  - Supplement to GPS Guidance

- **Robotics**
  - Industrial robots
  - Toy Robots

- **Weapon Systems**
  - Smart Artillery Shells
  - Missile Guidance

- **Platform stabilization**
  - Camera
  - Machinery
  - Wheelchair stabilization

- **Computer/Consumer**
  - Input devices
  - Handheld GPS
Conclusions

- Inertial Sensor Designs are Mechanical Structures of Mass Supported by Springs
- Inertial Forces on the Mass Result in Displacement that is Sensed Capacitively
- New Trends in Applications for Motion Detection are Occurring in Hand-held Devices and Portable Devices
- Gyroscopes Vibrate an Accelerometer and Measure Coriolis Acceleration that Indicates Angular Rate
Questions  Please