Micromachined inertial sensors

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May 2nd, 2005

Micromachined accelerometers
Basic principle of an accelerometers

Accelerometer in your car!

\[ \tan \theta = \frac{ma}{mg} = \frac{a}{g} \Rightarrow a = g \tan \theta \]

Basic principle of (MEMS) accelerometers

\[ m \ddot{x} + bx + kx = ma \]

At steady state...

\[ kx = ma \Rightarrow x = \frac{m}{k} \] Sensitivity

But, ...

\[ f_{resonance} = \sqrt{\frac{k}{m}} \] Resonance frequency

High sensitivity implies low resonance frequency;

Low resonance frequency implies small operational range.

\{ \text{Tradeoff is necessary} \}
Effect of damping

\[ \frac{m}{k} \]

\[ b < 2\sqrt{km} \] under damping/resonating

\[ b > 2\sqrt{km} \] over damping

\[ b = 2\sqrt{km} \] Critical damping

Over-damping reduces the useful frequency range.
Under-damping causes peaking that may lead to mechanical failure.
Thus, damping is usually necessary but not too much or too little.

Range vs. bandwidth

<table>
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<th>Bandwidth (Hz)</th>
<th>Range (g)</th>
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- Shock waves and ballistics
- Airbag
- Biomedical
- Vibration and modal analysis
- Acoustic emission
- Seismometry
- Inertial navigation
- Microgravity

G.K. Ananthasuresh, Indian Institute of Science, Nov. 2004
What do you measure and how?

- A MEMS accelerometer contains a spring and a mass; and some damping.
- The displacement of the mass needs to be measured.
  - Directly as displacement
  - Or indirectly using strain in the structure
  - Or by some other indirect means
- Some actuation is necessary for self-test capability

Micro-accelerometers differ in the sensing (and actuation) mechanism.

Eight ways of detection of acceleration

(Esahi, 1992; Chap. 9, Sensors: A Comprehensive Survey, Bau et al. (ed.))
a. Piezoelectric

Inertial force on the piezoelectric pad induces charge.
Accumulated charge is calibrated for acceleration.
Leakage of charge causes problems in its measurement.
Easy to fabricate.

A Piezoelectric accelerometer

From 1980!
Chen et al.
(Howe and White group at U. C. Berkeley)
Uses ZnO for the piezoelectric effect.
Couples the generated charge to the gate of a depletion-mode, p-channel MOS transistor.
Anisotropic etching.
Integrates electronics.
Good linearity up to 100g in measured performance.
b. Piezoresistive

Diffused piezo-resistive layer on a cantilever beam.
Inertial force on the seismic causes the beam to bend.
The strain in the beam changes the resistance of the piezo-resistor.
Used in some commercial accelerometers.

Daimler Benz's piezoresistive accelerometer

Integrates electronics with the piezoresistive sensing element.
Electronics fabricated with CMOS with electrochemical etch-stop.

After bonding for the cap.
Plastic package.
c. Resonant mode sensing

The spring-mass system is excited near resonance condition.

The acceleration-induced stress shifts the resonance frequency.

The frequency-shift is calibrated for acceleration.

Both excitation and detection are needed.

Resonant mode micro-sensors have advantages that are exploited in MEMS.

d. Capacitive

Acceleration-induced displacement of the seismic mass is sensed capacitively.

Used in commercial micro-sensors.

Capacitance-change is very small (fraction of picoF).

To reduce parasitic effects, electronic circuits are usually integrated with the mechanical element.
Hitachi’s capacitive accelerometer

Special timed etching.
Bulk-micromachined.

e. Optical wave guide based sensing

The intensity of light through the optical wave guide is modulated by the inertial force on the seismic mass due to acceleration.
f. Hall effect based

Uses Hall effect to sense the displacement of the seismic mass. Amenable for microfabrication.

In fact, Hall coefficient is five orders of magnitude larger in semiconductors as compared with metals.

And, Hall voltage is inversely proportional to the plate thickness—another advantage in favor of miniaturization.

g. Magnetic

Magnetic induction-based sensing of the displacement of the seismic mass.

Senses lateral acceleration when mounted on a surface.
h. Any odd way you can imagine!

- Just an acceleration switch—whether acceleration has occurred or not.
- Measures lateral acceleration.
- It could be a nice movement sensor.
- Creation and retention of bubbles is easy in MEMS.

Some more points

- There are several other ways of detection.
- How about one without any moving parts? There is one like that!
- Single-axis or multiple axes?
- Cross-axis sensitivity?
- Over-range protection?
- Direct mode
- Force-feedback mode
**Force-feedback mode**

As opposed to open-loop measurement of displacement, force-rebalance ("servo") closed-loop technique could be used.

It has better sensitivity.

But actuating element is used to apply a force to keep the seismic mass stationary.

Closed-loop circuitry is also needed ➔ more complexity in electronics.

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**Electrostatic force-feedback**

With electrostatics, actuation force is readily available.

Widely used in MEMS inertial sensors, especially in micro-accelerometers.
Electromagnet-force feedback

Magnetic force is larger than electrostatic force.

But, more complications in microfabrication.

Sensitivity in force-feedback mode

\[ m\ddot{x} + b\dot{x} + kx = ma - F_f \]
\[ \left( ms^2 + bs + k \right) X(s) = mA(s) - F_f(s) \]

\[ E(s) = \frac{A(s)Gm}{ms^2 + bs + k + GB} \approx \frac{A(s)m}{B} \text{ if } \frac{ms^2 + bs + k}{B} \ll G \]

Sensitivity = \( \frac{m}{B} \) which is independent of the stiffness.

A circuit parameter
Piezoresistive accelerometer

Piezo-resistor element is diffused into silicon.

A reference resistor is also included in the same process for compensating the temperature effects.

Model for analysis

Capacitive accelerometer

Differential capacitive sensing.

(Ura and Esahi, 1991)
Analog Devices's capacitive accelerometer

Surface-micromachining integrated with CMOS.

Self-test capability

Self-test capability is very important for automotive applications.

"Creation" of inertial force requires an actuating element.

This NovaSensors piezo-resistive accelerometer uses thermal actuation for self-test.

Notice the power required!
Over-range protection

Some designs add more mass and decrease damping also.

Ford's capacitive accelerometer
Michigan's dissolved wafer process

FIB-aided accelerometer

Focused ion beam can be used to deposit as well as etch. Features of the size tens of nanometers can be obtained. Usually used in chip-repair.

Lateral-side fluid damping is not as complicated or as pronounced as vertical squeezed film damping.

Very small gaps are useful to enhance the capacitance signal as well as in electrostatic force-feedback.

An ultra-sensitive accelerometer
**Tunnelling effect accelerometer**

Very precise measurement of displacement. ➔ better sensitivity of the accelerometer.

A 0.01 nm displacement of the tip can cause a 4 to 5% change in the tunnel current.

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**Accelerometer with no moving parts**

A heater in a cavity filled with a gas.

Two temperature-sensors (thermocouples) on either end of the cavity.

Acceleration-induced convection changes the temperature across the cavity.

0-7 g has been measured.
Micro-accelerometers in toys

Three-axis accelerometer (Sandia)

Two case studies

- **ADXL50**: A capacitive accelerometer—commercially available
  - Emphasis on process and modeling
- **RASTA**: A piezoresistive real self-test capable accelerometer—academic laboratory prototype
  - Emphasis on packaging, testing, and calibration

ADXL50: Analog Devices accelerometer

- Differential capacitive sensing
  - Interdigitated combs with lateral motion
- Open-loop
- With self-test
  - Electrostatic actuation
- Integrated electronics in iMEMS process
- Has a wide range of accelerometers of this kind
ADXL50: Mechanical and Electronic details

Analod Devices developed iMEMS process for their inertial MEMS sensor. It combines CMOS with surface micromachining.

Mechanical components
753 um x 657 um

One of its version consisted of...
13 for electronics and
11 for mechanical components.

It combines...
MOS transistors,
Bipolar transistors,
And polysilicon structures.
Steps in iMEMS process

Interconnect region between the circuit and sensor element formed.

After deposition and patterning of the structural polysilicon.

iMEMS process steps (contd.)

Opening of contact holes and metallization in the circuit part.

After releasing the mechanical structure.
### ADXL50: Specifications

- **Range**: +/- 50g
- **Sensitivity**: 38 mV/g
- **Transfer function**: $V_{out} = 0.5V_s \pm \alpha + \beta aV_s$
- **0g bias voltage**: $0.5V_s \pm 0.35 V$
- **Temperature range**: -40 to +85 deg C
- **Supply voltage**: 4 to 6 V
- **Nonlinearity**: 0.2%
- **Bandwidth**: 1 KHz or customer choice
- **Transverse sensitivity**: 0.2 g
- **Resonance frequency**: 24 kHz
- **Drop test**: 1.2 m
- **Package alignment error**: +/- 1 degree

### Highlights of modeling

$$C_{sense} = 42 \frac{\varepsilon_0 hL}{g_0 \pm y}$$

$$C_{sense} = 60 \frac{\varepsilon}{fF} \left(1 \pm \frac{y}{g_0}\right) \approx 100 \frac{fF}{v}$$

$$k = \left(\frac{\pi^2}{6}\right) \left(\frac{Ewh^3}{8L^3}\right) = 5.6 \frac{N}{m} \leftrightarrow 5.4 \frac{N}{m} = k_{\text{reported}}$$

$$Q = \text{Quality factor} = 120, 34, 3.5, 5$$

SQFD  CFM  Detailed 3-D numerical modeling
RASTA

Real-Acceleration Self-Test Accelerometer

Piezoresistive sensing & magnetic shaking

Built-in shaker

Steve Reyntjens's PhD thesis at K. U. Leuven
Advisor: Bob Puers

Accelerometer chip: 6 mm x 6 mm

Initial packaging problems

The chip was glued to the ceramic substrate.
The bending of cables caused significant stress in the ceramic substrate and the accelerometer.
Finalized packaging of RASTA

Post FIB processing to release the frames.

Test rig for RASTA
Main points

- The range of micro-accelerometers proves that there are many ways to do one thing.
- Commercial devices exist; indeed there is competition among different companies.
- Micro-g accelerometers are yet to be researched fully.
- Accelerometers, being the flagship application since the inception of MEMS, embody most of the microsystems' principles.