The Physics behind the Probeware: How does an Accelerometer Work?

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Intriguing Application: Rocket Sled Testing

- John Stapp, MD, PhD
- “G-Whiz” rocket sled
- 15 g for 0.6 s (pictured)
- 46.2 g peak (1954)
What does an Accelerometer Measure?
What are Accelerometers really good at?
What are they bad at?
All Accelerometers have:

- A Mass
- A Spring Suspension
- Some Damping
- A Displacement Sensor
Accelerometer Theory of Operation

\[ \sum F = ma \]

\[ Z = X - x \]

\[ Z_0 = \frac{m \omega^2 X_0}{m \omega^2 - k - i \omega b} = \frac{\omega^2 X_0}{\omega^2 - \frac{k}{m} - \frac{i \omega b}{m}} \]
Interesting Cases to Consider

• $b = 0$ undamped
  • As $\omega \to \omega_0$, output $Z \to \infty$
  • Accelerometers are usually designed with some damping to avoid this outcome

• $\omega < \omega_0$ expression simplifies to:

$$Z_0 \approx \frac{\omega^2 X_0}{\omega_0^2} = \frac{A}{\omega_0^2}$$

  • Displacement of mass is proportional to acceleration $A$

• $\omega > \omega_0$ expression simplifies to:

$$Z_0 \approx X_0$$

  • Good for a seismometer, where we want to measure displacements
Optimized Accelerometer Output
Transduction principles

• Capacitance change
• Piezoresistance- strain gauge
• Piezoelectric
• Magnetic
• Thermal
Transduction principle - capacitance of parallel plates
Lots of parallel plates increase the capacitance change
Basic capacitive accelerometer design
ADXL202 Example

Structural Thickness = \(\sim 2 \mu m\)

Mass = \(~ 1 \times 10^{-10} \text{ kg}\)

Suspension Stiffness = \(\sim 1 \text{ N/m}\)

Resonant Frequency = \(\sim 10 \text{ kHz}\)

Detectable Acceleration = \(0.5 \text{ mg/}\sqrt{\text{Hz}}\)
Thermal fluctuations in Accelerometers

• Thermal fluctuations in micromechanical systems exert a noise force, indistinguishable from inertial forces.

• The minimum detectable acceleration from thermal noise is

\[
A_n = \sqrt{\frac{4 \ k_B \ T \ \omega_0}{m \ Q}}
\]

\[
\omega_0 = 10 \ kHz, \ m = 0.1 \ \mu gm, \ Q = 0.7
\]

\[
A_n = 0.3 \ mg/\sqrt{Hz}
\]
ADXL202 Example

Structural Thickness = ~ 2 µm
Mass = ~ 1 x 10^{-10} kg
Suspension Stiffness = ~ 1 N/m
Resonant Frequency = ~ 10 kHz
Detectable Acceleration = 0.5 mg/√Hz
Detectable Displacement = 0.005 Å/√Hz
Detectable Force = 0.5 pN/√Hz

Figure 17. The ADXL05 Sensor Momentarily Responding to an Externally Applied Acceleration
ST Micro
LSM330DLC
ST Micro LSM330
Bosch BMA250
Bosch, STM, ADI, others
Bosch Assembly
Thermal Accelerometer
MEMSIC MXA2050A
Bosch Accelerometer Video

• https://www.youtube.com/watch?v=RLQGZl0lpjQ
The PocketLab Voyager Accelerometer in Action