Capacitive Interface Electronics for Sensing and Actuation

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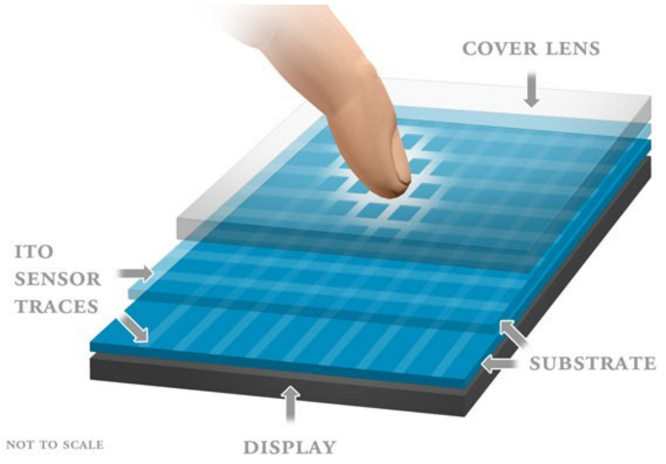
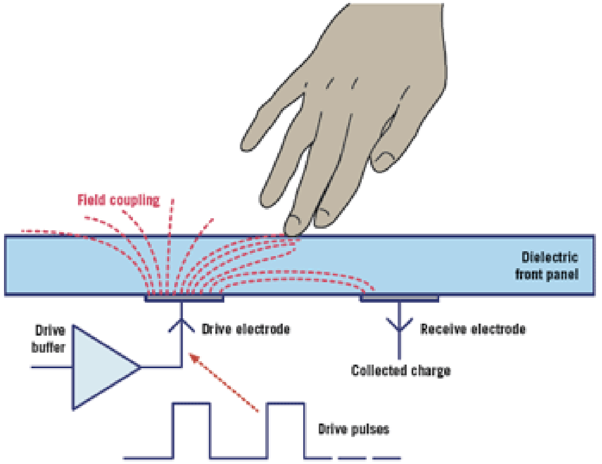
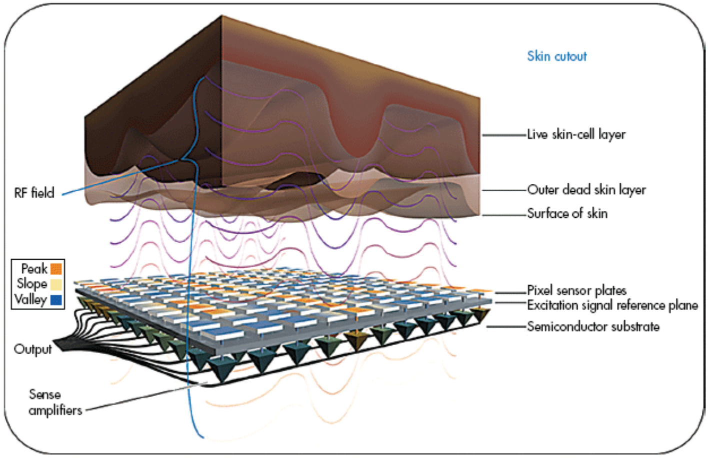
Outline

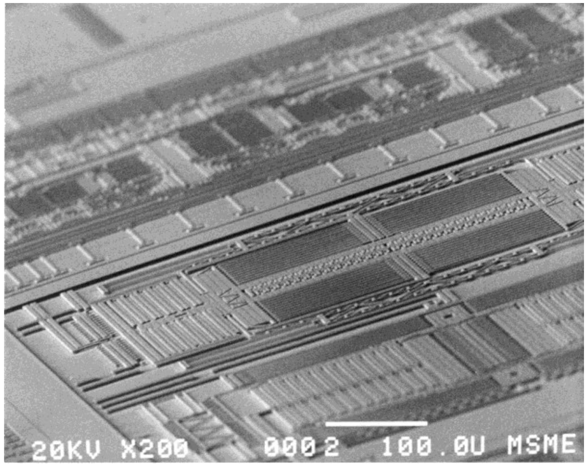
- Capacitive Sensors
  - Applications
  - Displacement sensors
- Readout electronics
  - Sensor interface
  - Circuit topologies
  - Electronic noise
- Feedback
  - Electrostatic force feedback
  - Stability
  - Sigma-delta conversion
- Conclusions

Applications

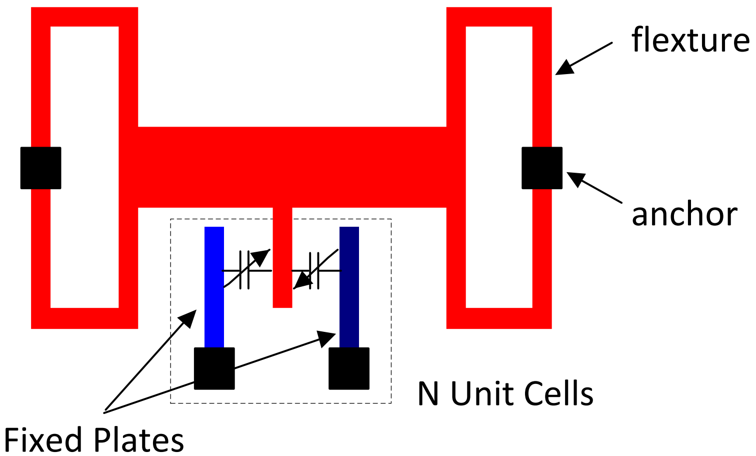






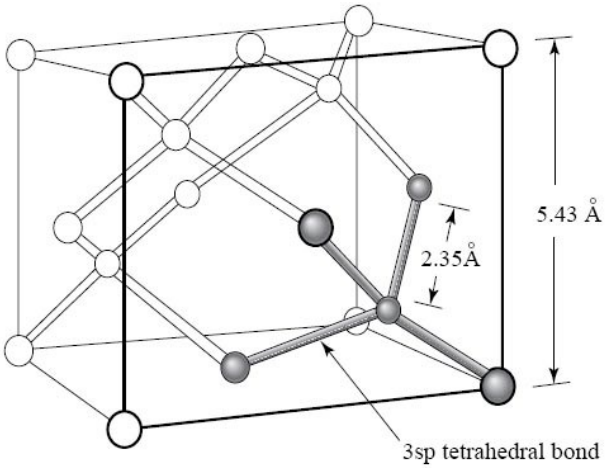


Accelerometer

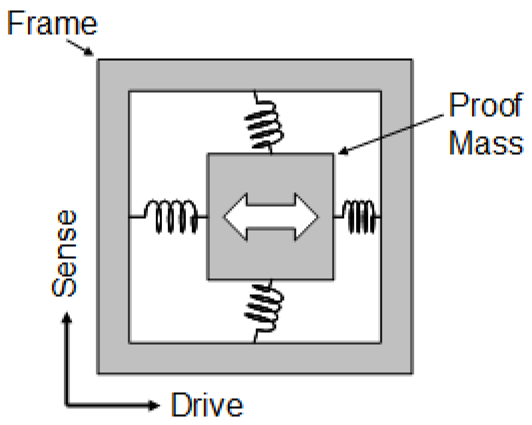


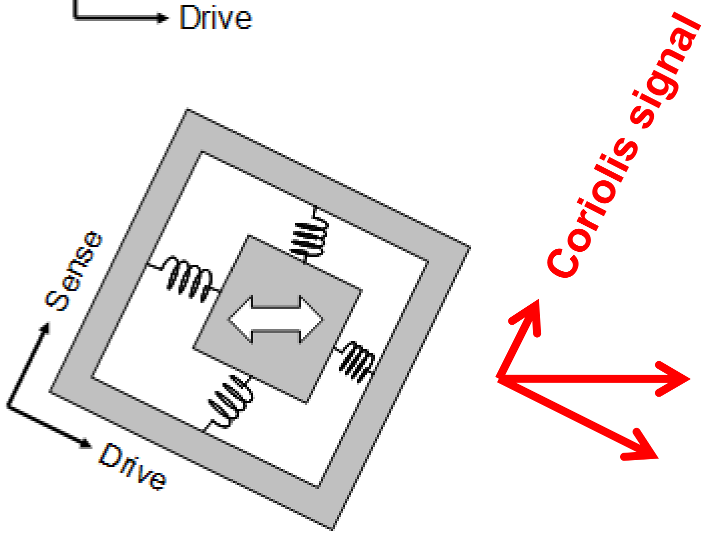
$$x = \frac{a}{\omega^2} = \frac{1\text{mG}}{(2\pi \times 10\text{kHz})^2}$$

$$= 2.5\text{pm} = \frac{1}{40}\text{Angstrom}$$



Gyroscope

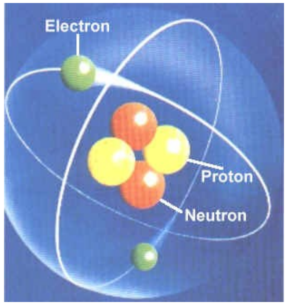




- Vibrate along drive axis with oscillator @ f_{drive}

- Detect vibration @ f_{drive} about sense axis with accelerometer

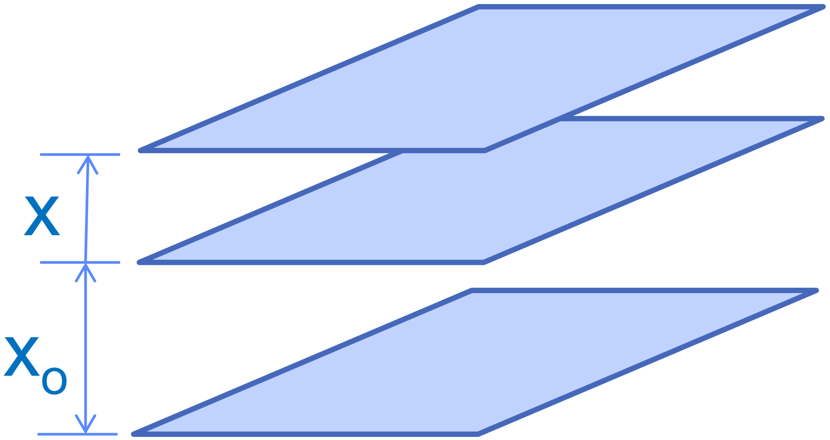
  $x_{typ} \cong 20$ fm



Classical radius of electron: 2.8 fm

Capacitive Displacement Sensors

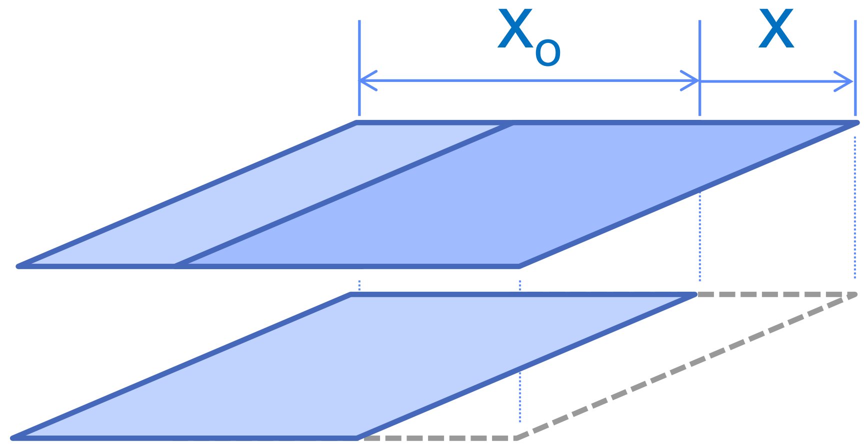
Gap closing



$$C(x) = C_o \frac{x_o}{x_o + x}$$

$$\frac{1}{C_o}\frac{dC(x)}{dx} = \frac{1}{x_o}\bigg|_{x=0}$$

Overlap



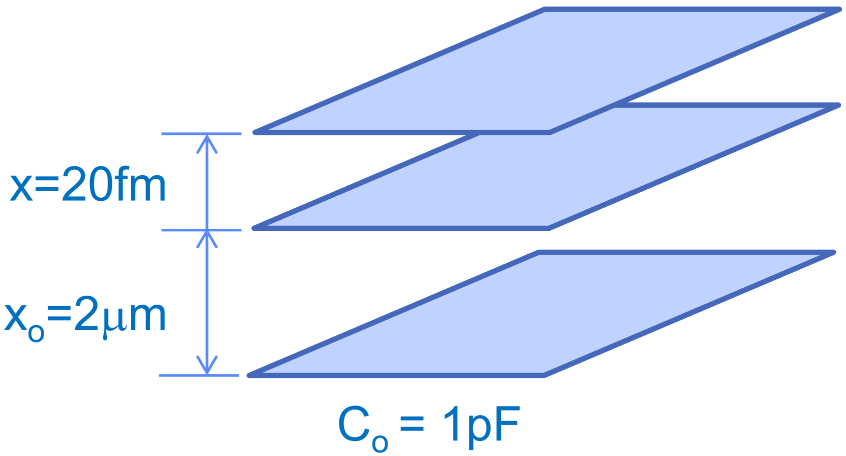
$$C(x) = C_o \frac{x_o - x}{x_o}$$

$$\frac{1}{C_o}\frac{dC(x)}{dx} = -\frac{1}{x_o}$$

Cap closing actuator has higher sensitivity

Capacitive Displacement Sensors

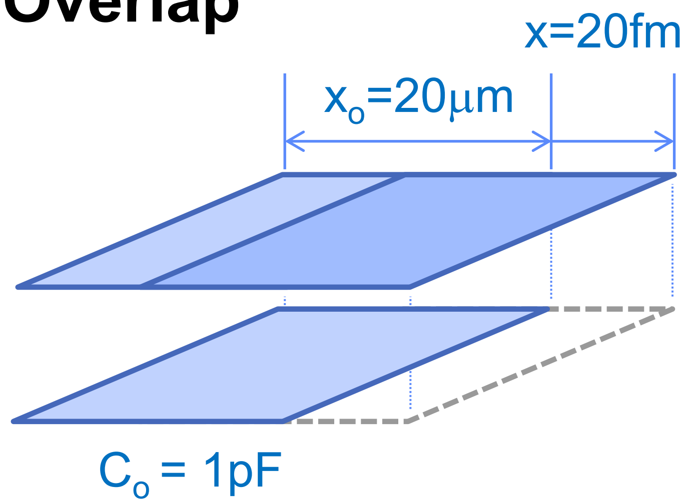
Gap closing



$$\Delta C_o = 10 \text{ zF} = 10^{-20} \text{ F}$$

- High sensitivity
- Limited travel range
- Nonlinear
- Pull-in

Overlap



$$\Delta C_o = 1 \text{ zF} = 10^{-21} \text{ F}$$

- Low sensitivity (large x_o)
- Large travel range
- Linear (first order)
- No pull-in (first order)

Alternative Geometries

Gap Closing Design
- high sensitivity
- small travel range

Overlap Sensor Design
- low sensitivity
- large travel range

Compromise

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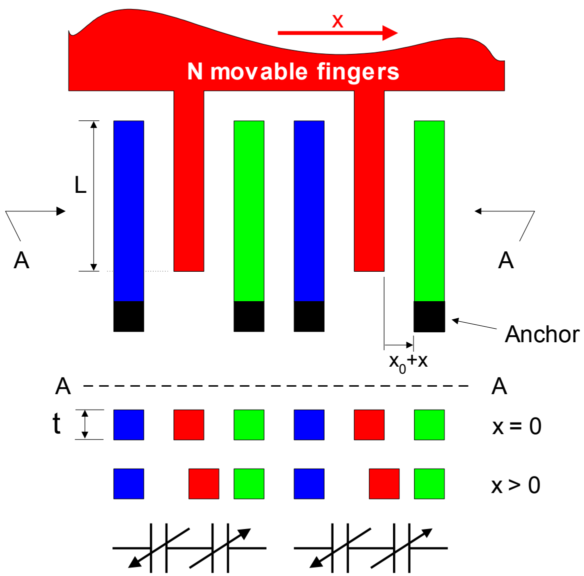
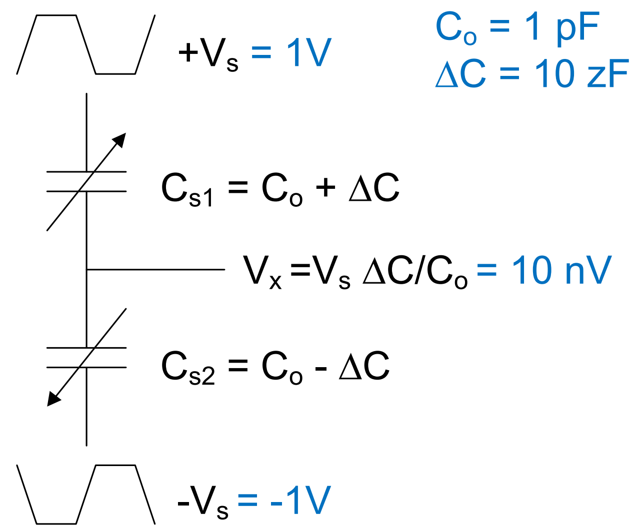
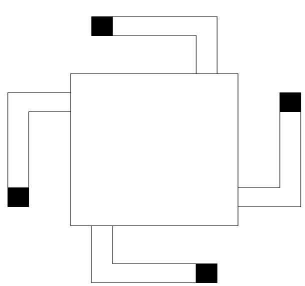
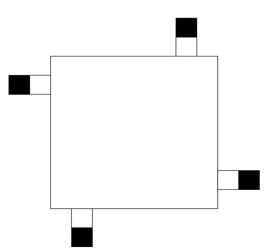
Capacitance to Voltage Conversion







sense capacitor C_s

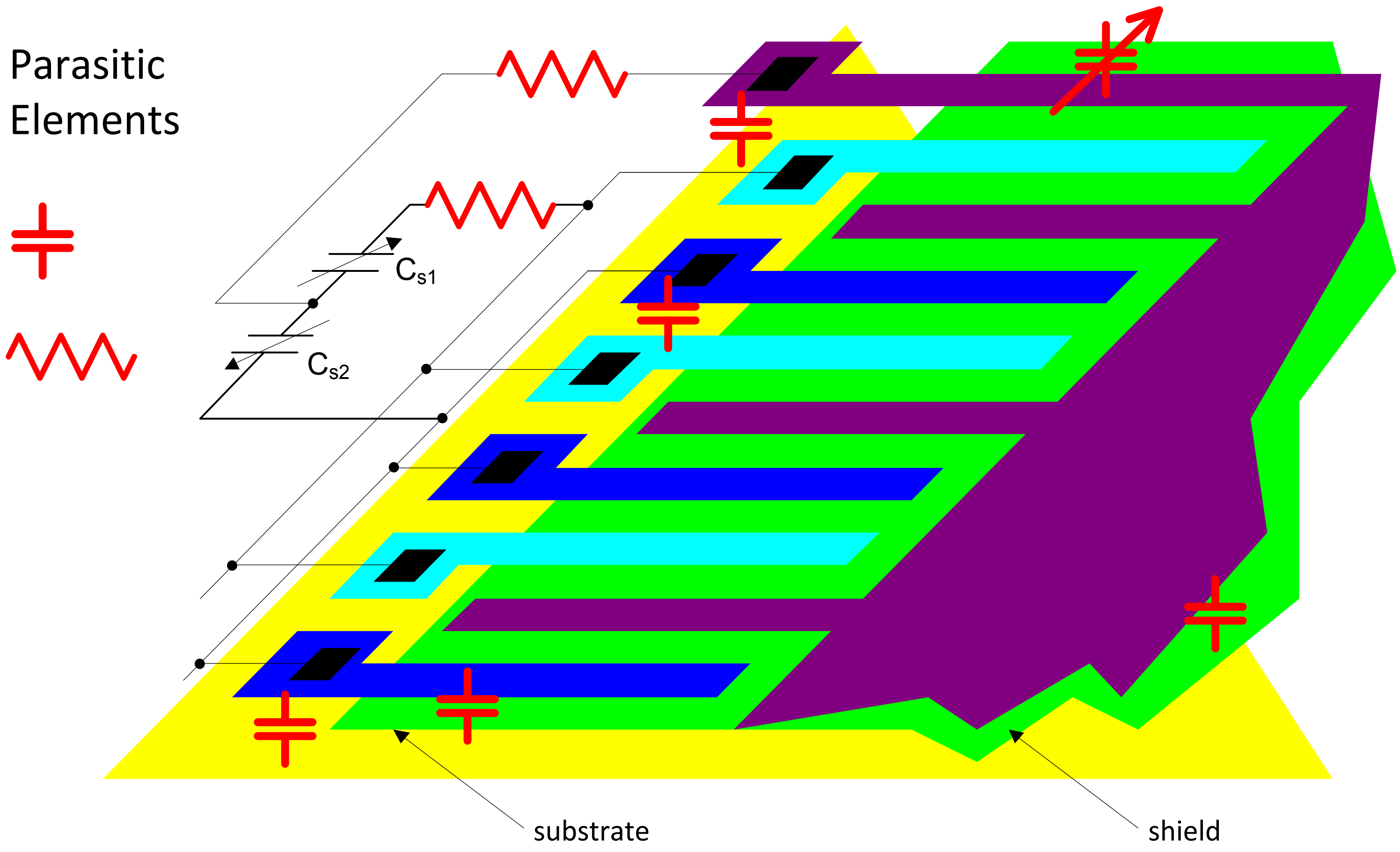


reference capacitor C_{ref}

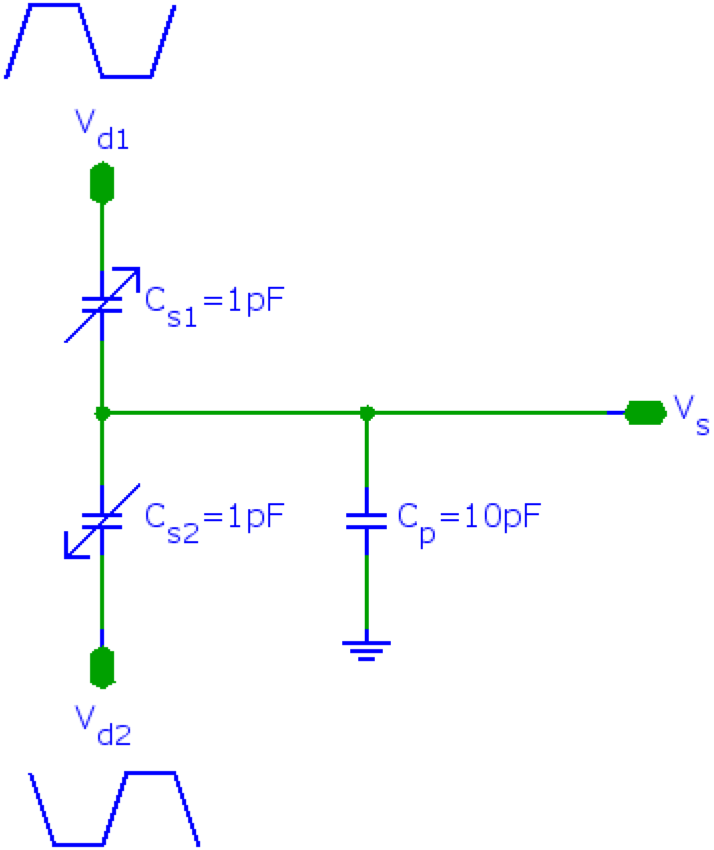
- maximize ΔC
- minimize C_o
- maximize V_s

Parasitics

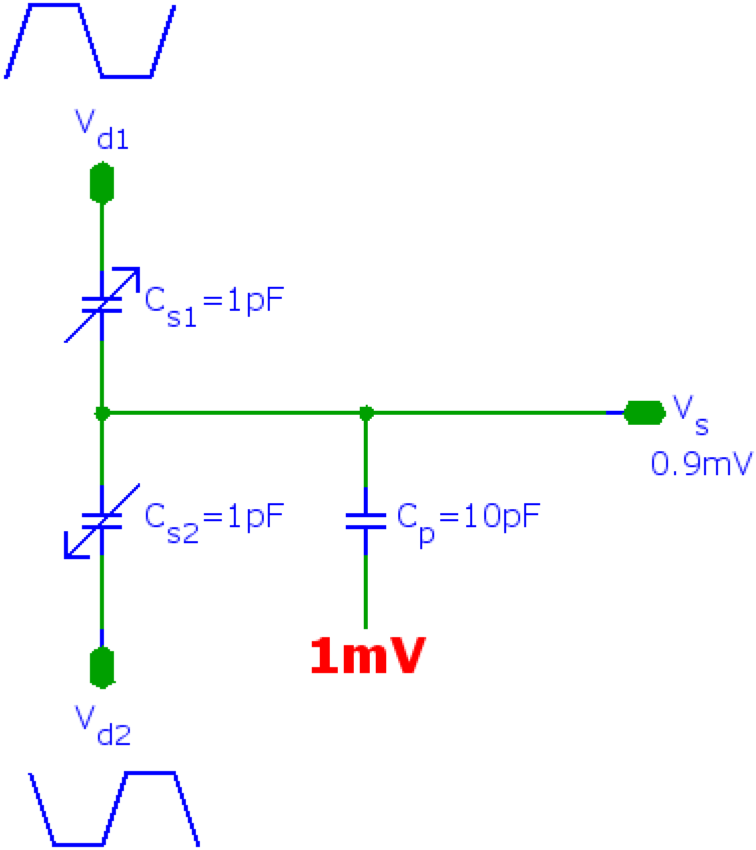
Parasitic Elements



Capacitive Transducer Interface

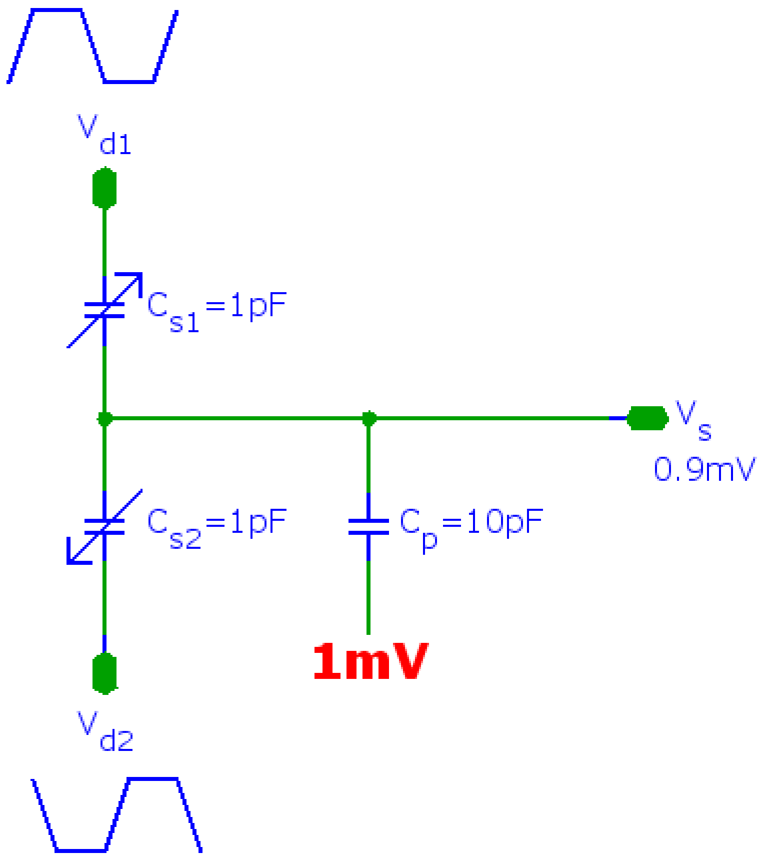


Interference

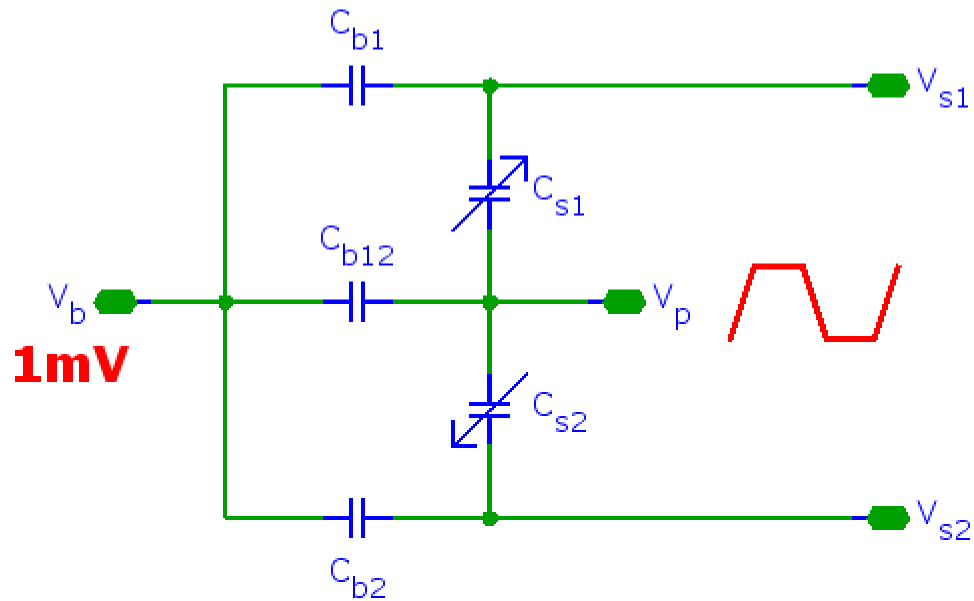


Differential Interface

Single-Ended



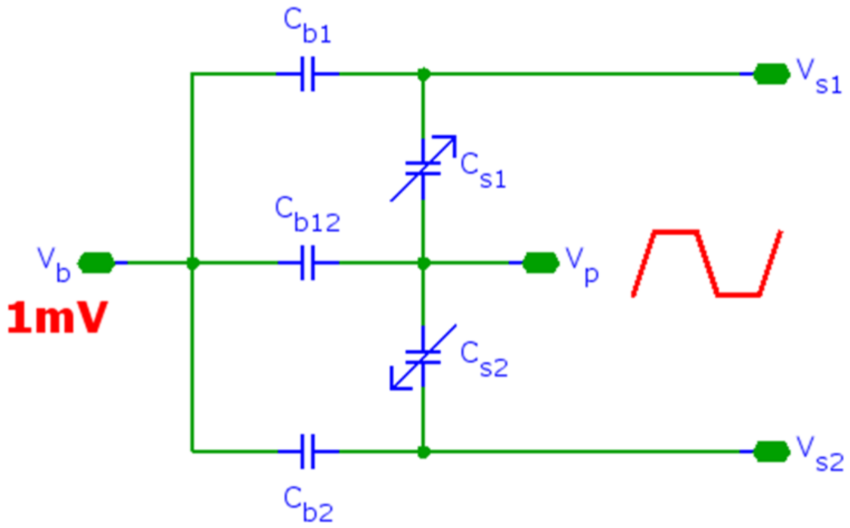
Pseudo-Differential



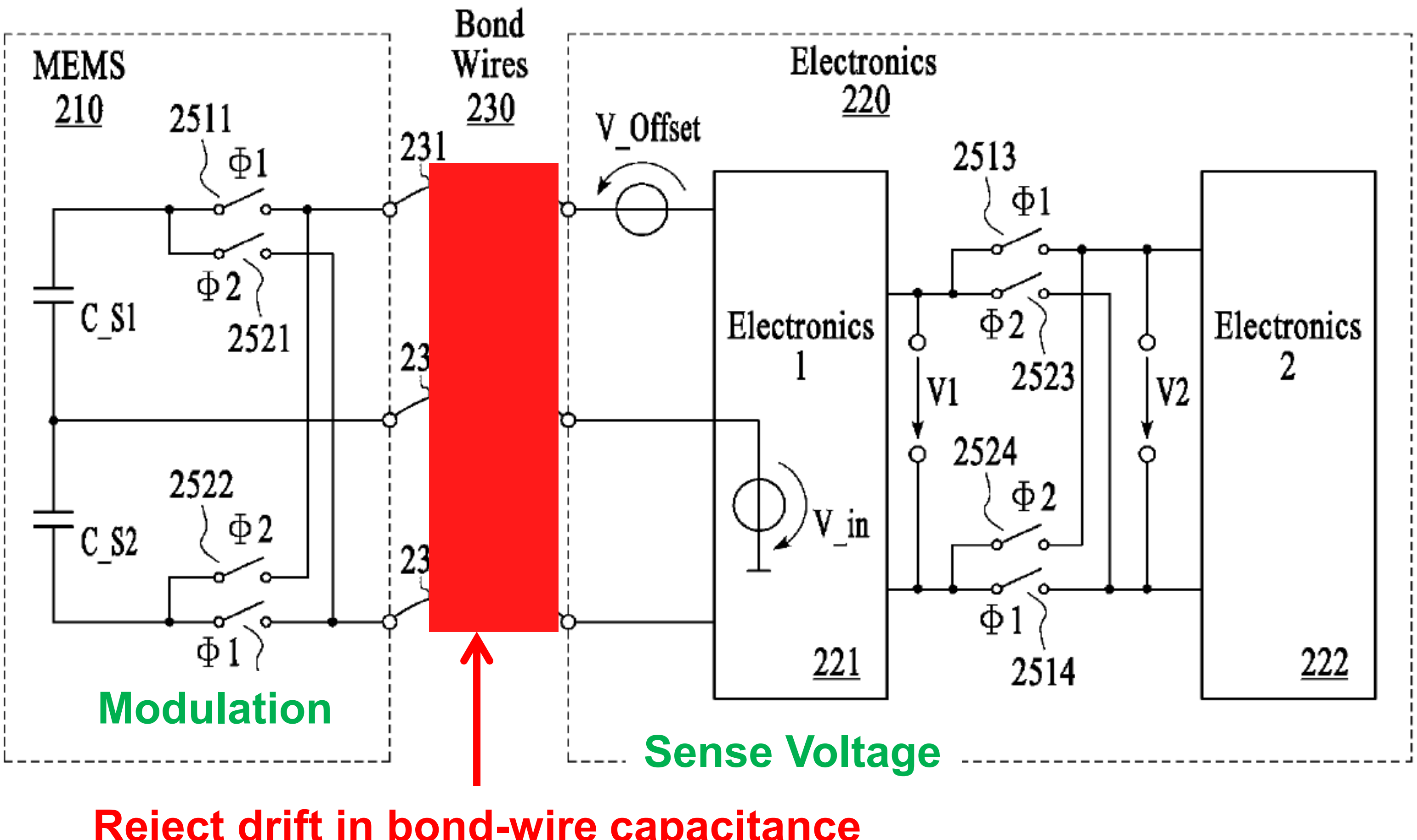
Interference → common-mode signal

Modulation

- Low frequency acceleration signal
  - Subject to low-frequency interference
    E.g. 1/f noise
  - Capacitors do not pass DC
- Solution: modulate signal <u>before</u> it can be corrupted

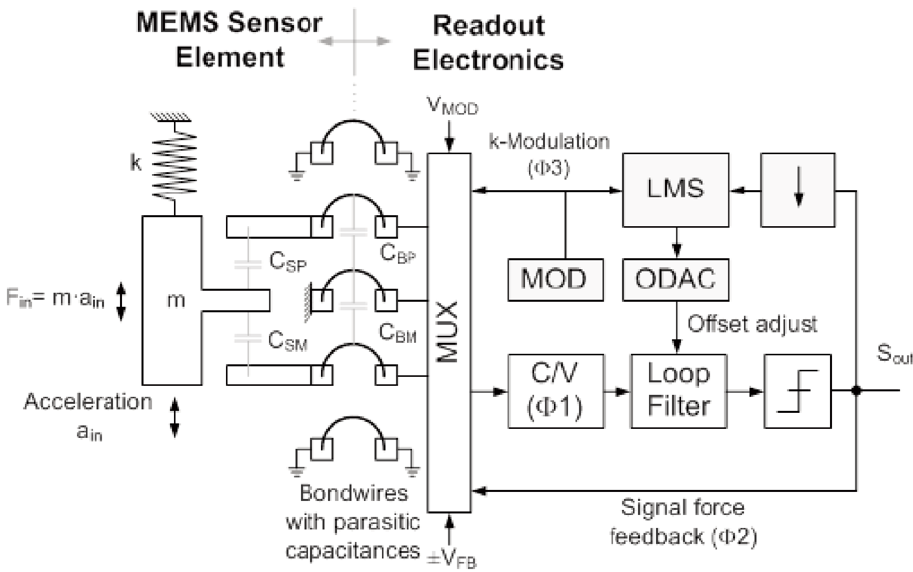


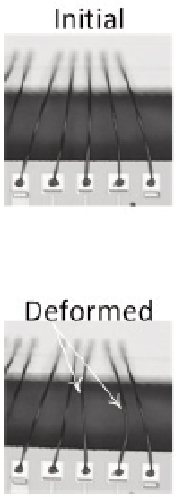
Modulation in 2-Chip Sensors

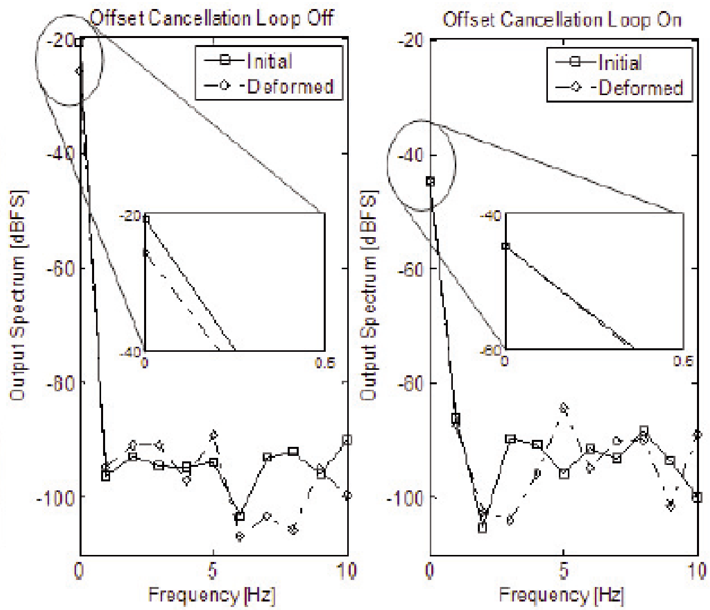


Ref: Lang et al, Cancelling low frequency errors in MEMS systems, 2009.

Mechanical Modulation



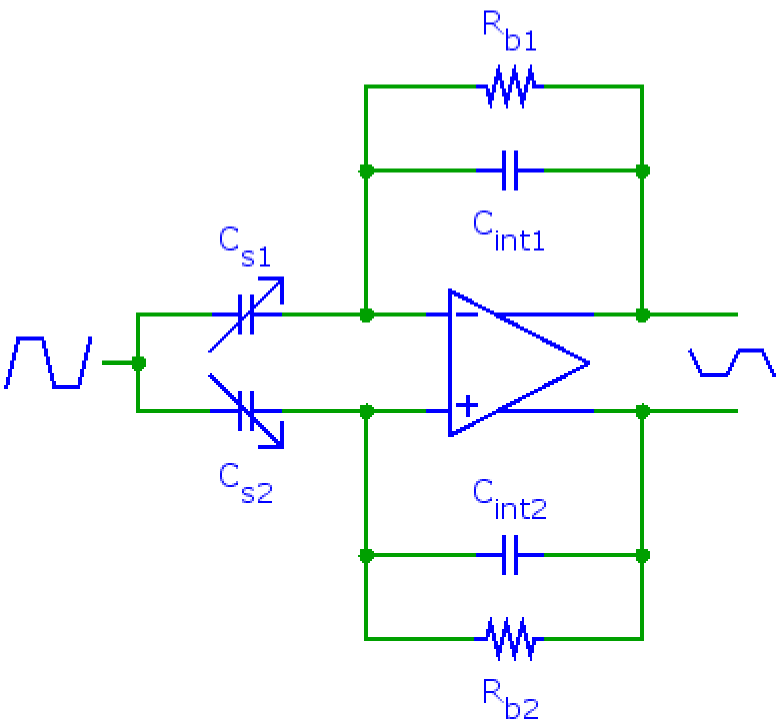




Ref: P. Lajevardi, V.P. Petkov, and B. Murmann, "A ΣΔ Interface for MEMS Accelerometers using Electrostatic Spring-Constant Modulation for Cancellation of Bondwire Capacitance Drift," in Digest ISSCC 2012, pp. 196-197.

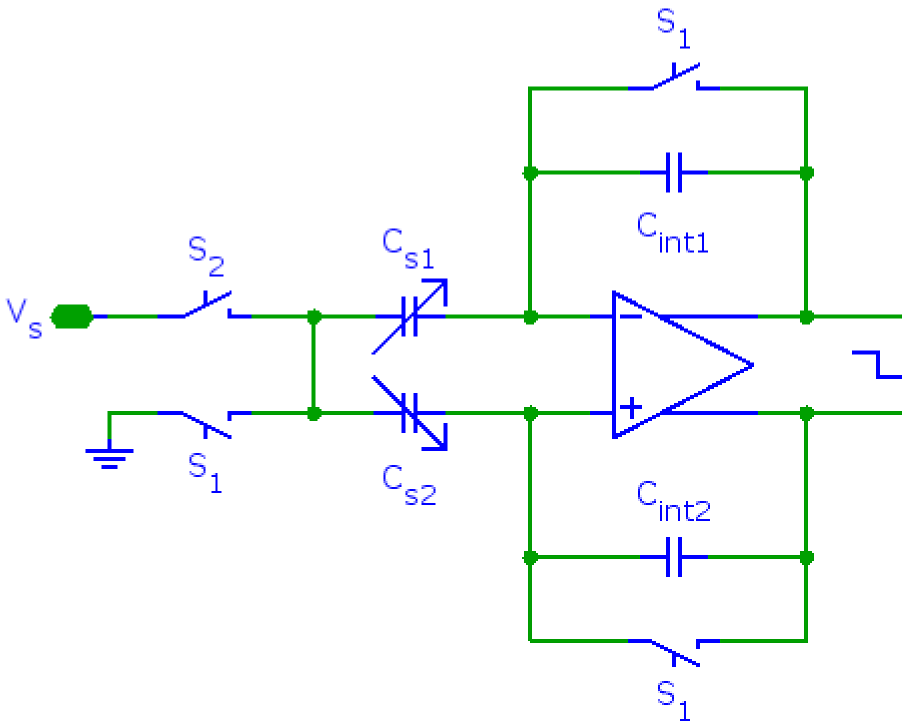
Capacitive Interface Circuits

Continuous Time



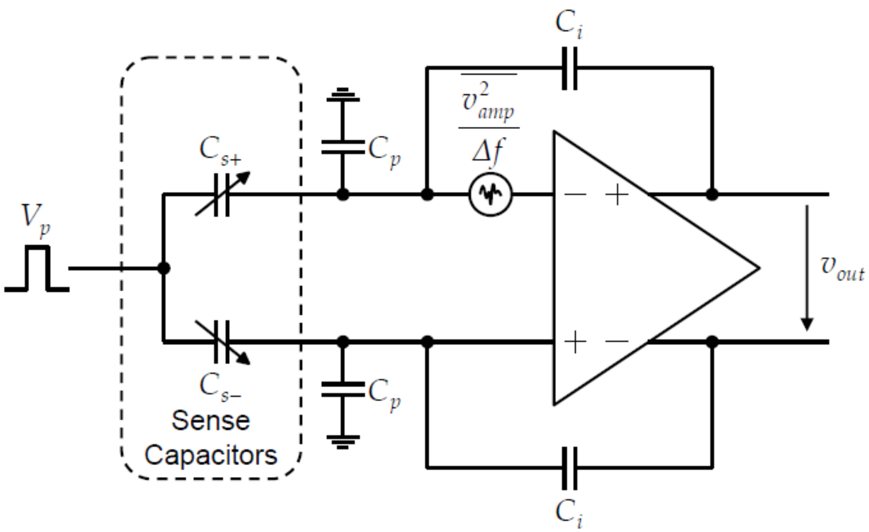
- Output modulated
- High valued bias resistor

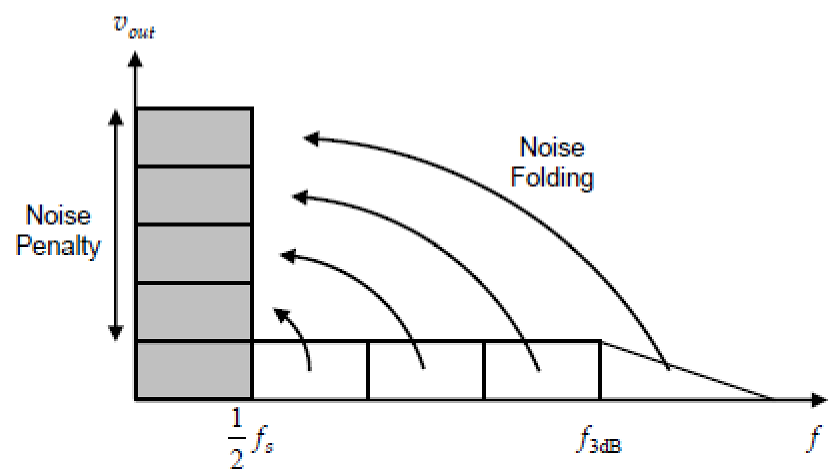
Sampled Data



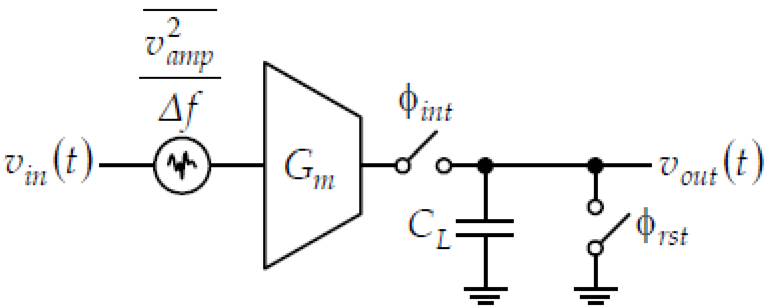
- No bias resistor, direct interface to ADC
- Noise folding

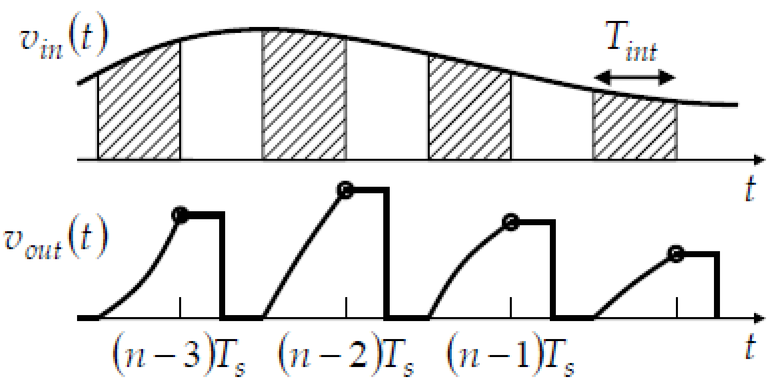
Noise Folding

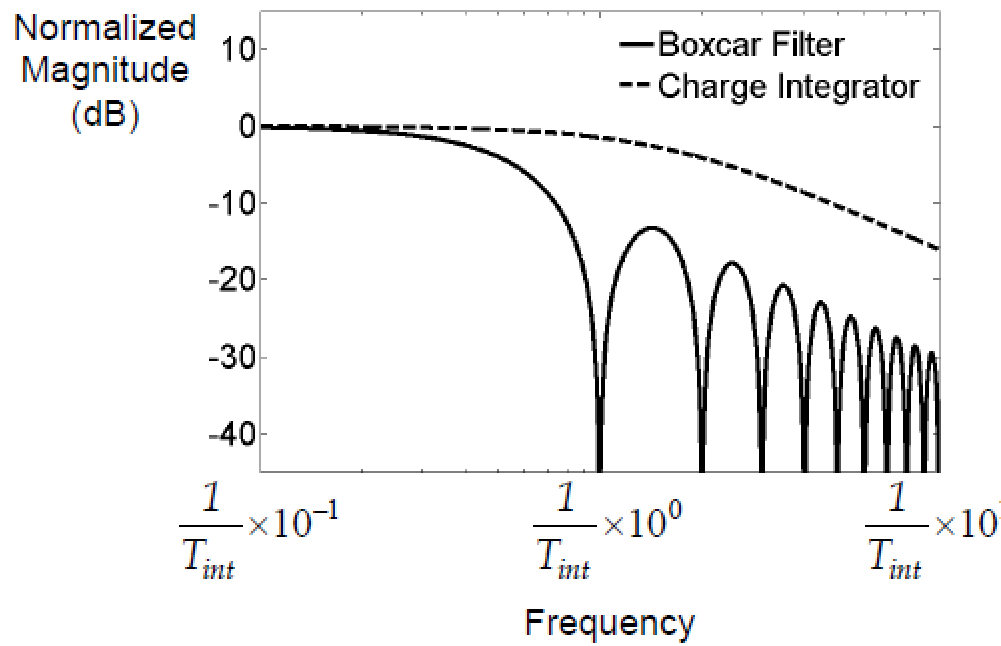




“Boxcar” Sampling







- ~ 10dB noise / power reduction possible
- sensitive to clock jitter & nonlinearity

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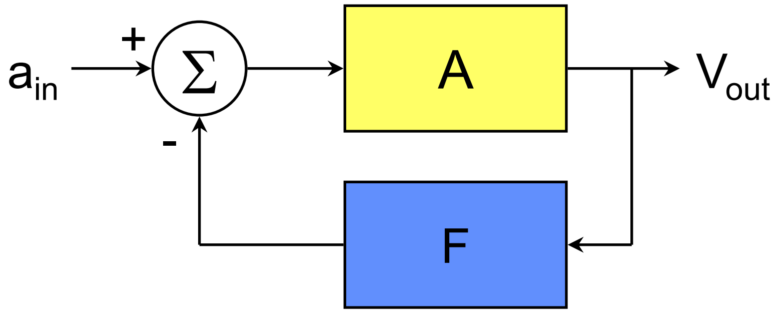
Electrostatic Force Feedback



Benefits:

- Reduced sensitivity to transducer nonlinearity
- Increased bandwidth (gyroscopes)

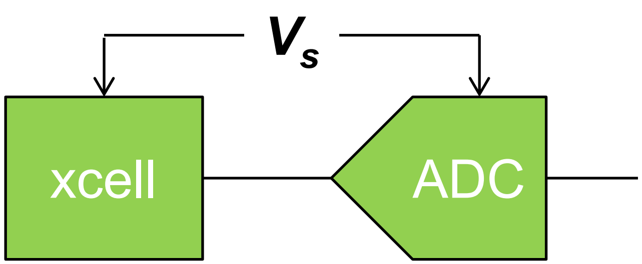
Challenges:

- Need accurate feedback force
- Stability
- Increased noise

Scale Factor

Openloop

$$V_{out} = -\underbrace{\frac{\ddot{}}{\omega_r^2}\,\frac{}{dx}}_{\Delta C}\;\frac{}{C_o}\;\frac{\ddot{}}{\omega_r^2}\;\frac{}{x_o}$$



$$D_o = \frac{V_{out}}{V_s}$$

$$\ddot{} \quad {}_o \quad \omega_r^2 x_o$$

ADC output   scale factor

Feedback

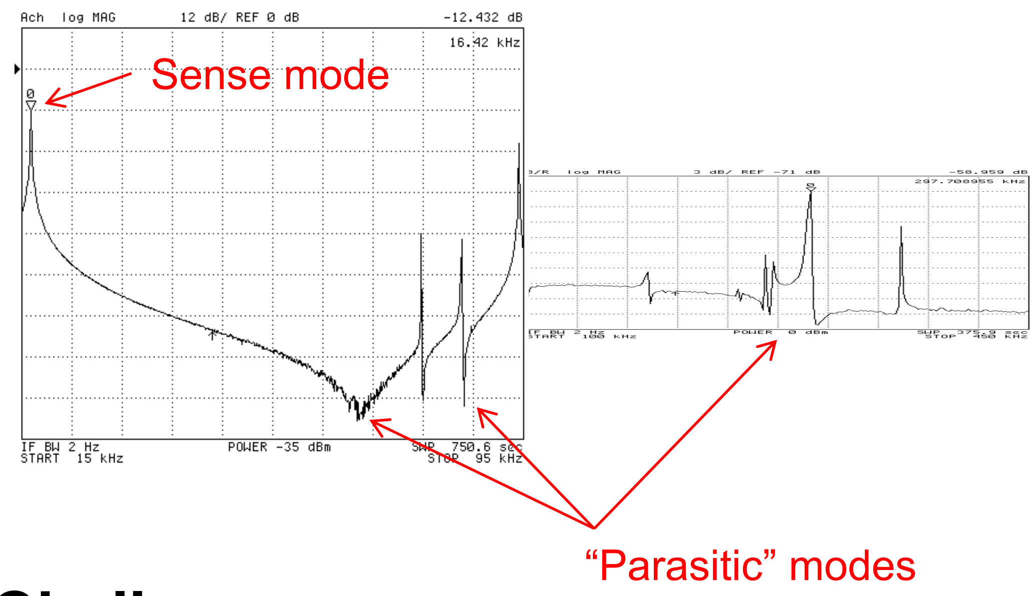
$$\underbrace{\frac{1}{}\frac{dC}{}V_{fb}^2}_{\text{feedback force}} = m\ddot{}$$

acceleration force

$$\ddot{} = \frac{}{2}\frac{dC}{dx}\cdot\frac{V_{fb}^2}{m}$$

- Final measurement depends on absolute voltage
- Need precision reference for good scale factor accuracy
- Feedback is nonlinear

Stability



typical high performance gyroscope frequency response

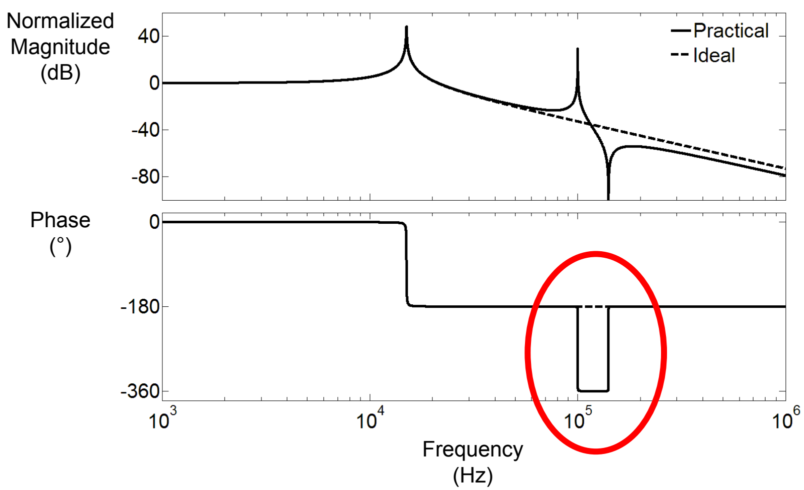
Challenges:

- 2^{nd} order system
- High Q → 180^o phase lag at resonance
- Higher order resonances
- Additional loop delay (e.g. DAC)

Feedback Actuator

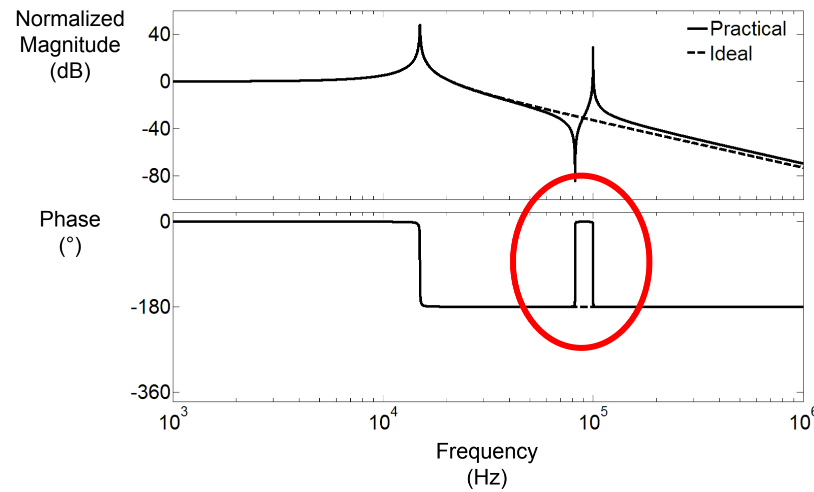
Non-Collocated

separate electrodes for sense and feedback



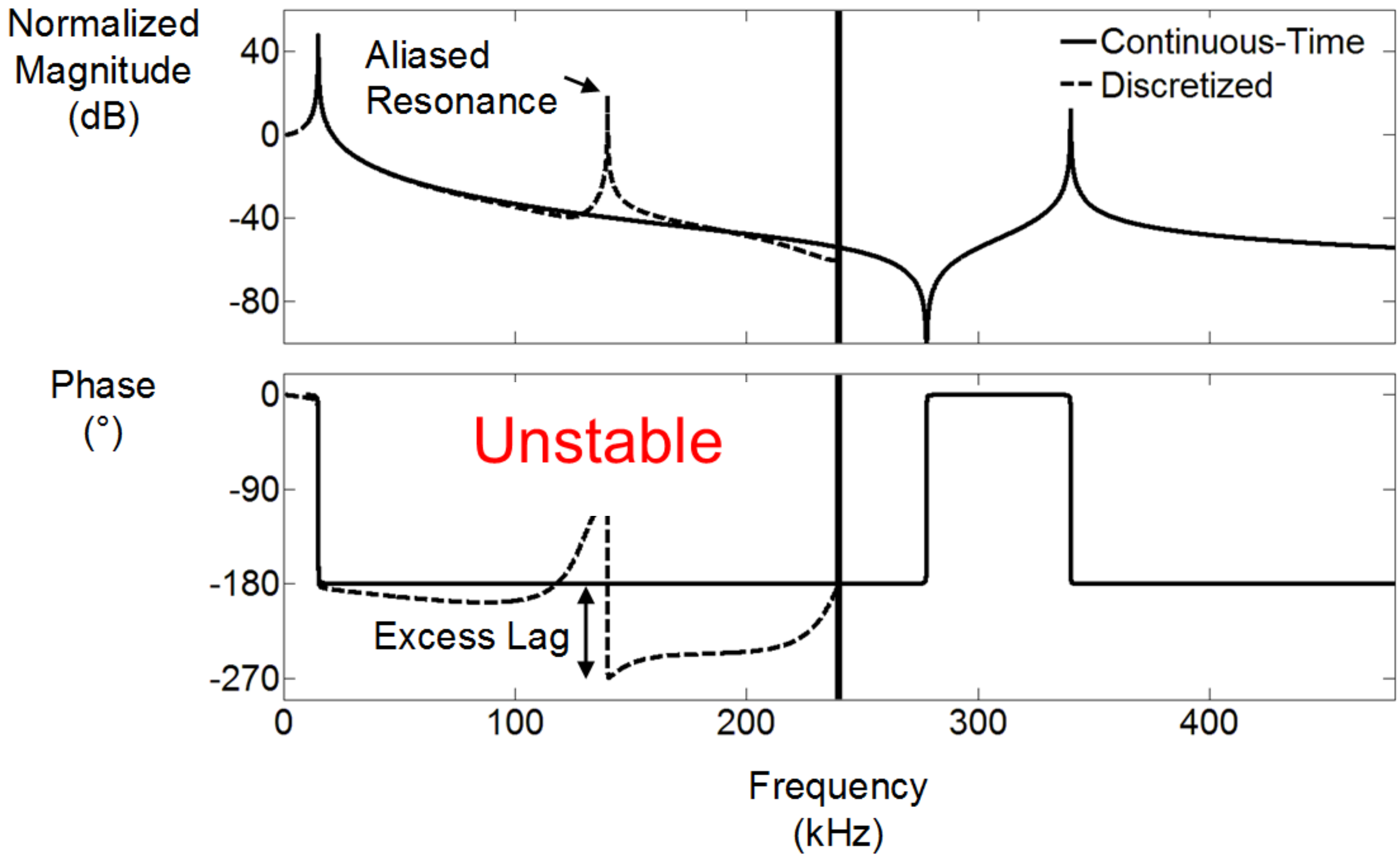
Collocated

same electrodes for sense and feedback

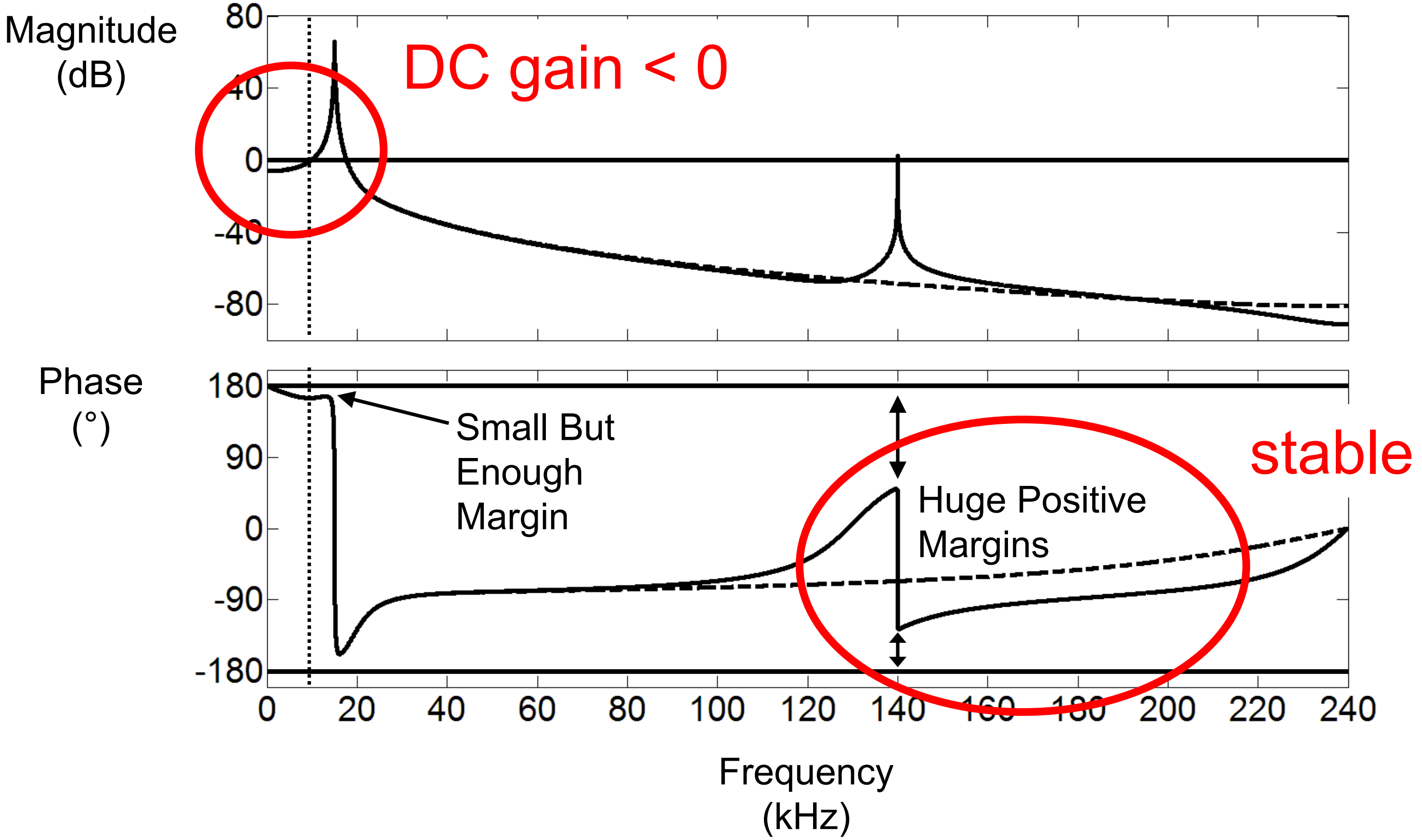


Stabilize with lead compensator?

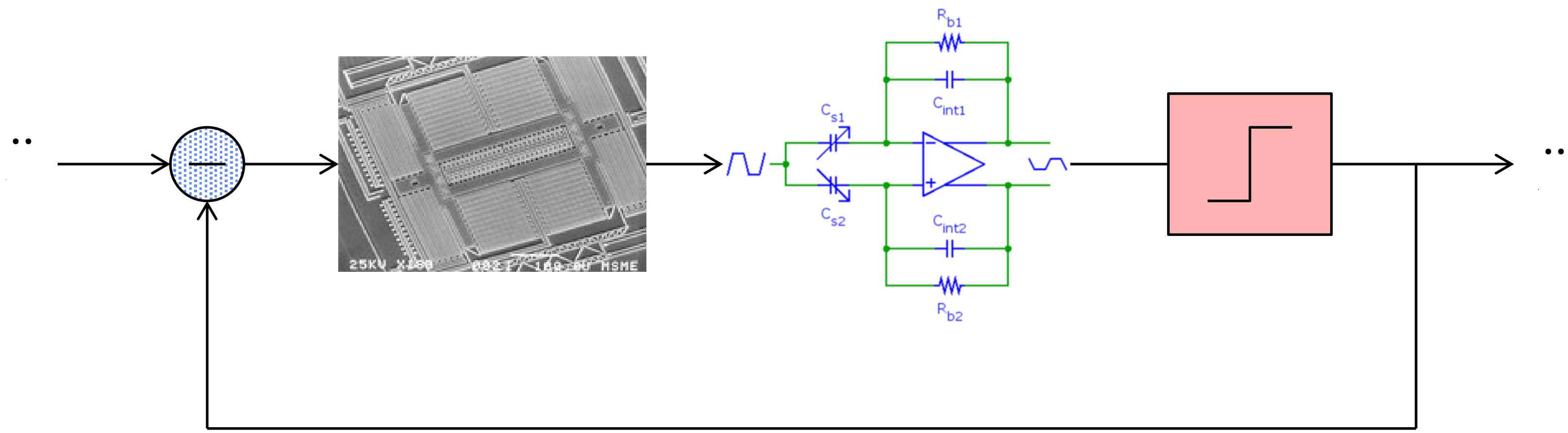
Sampled Data System Loop Gain



Positive Feedback

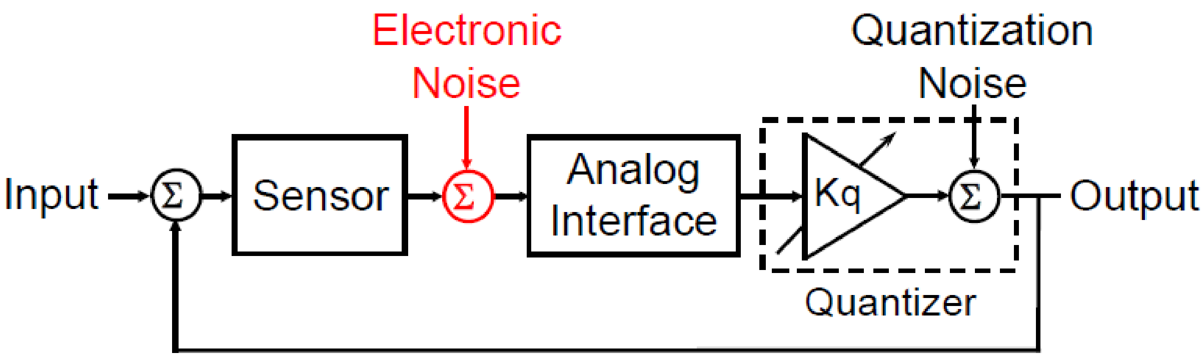


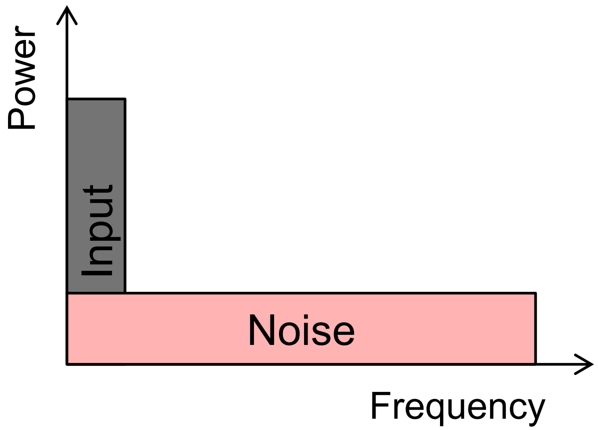
Sigma-Delta A/D Conversion

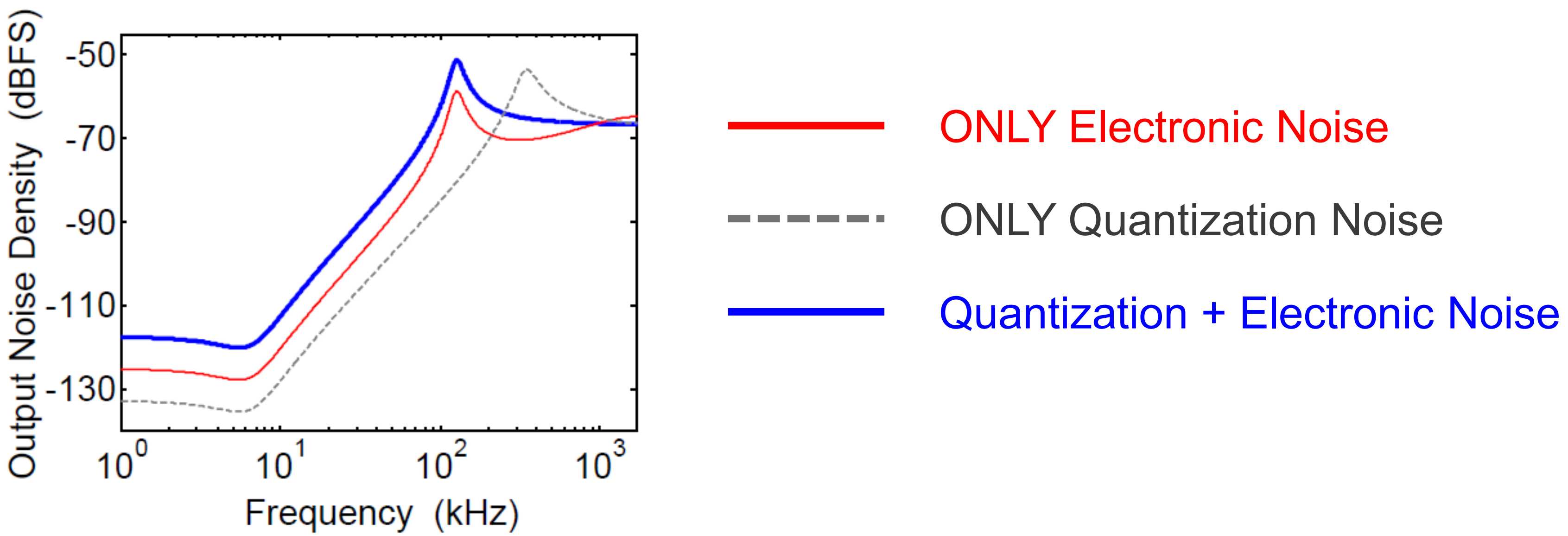


- Very low overhead: only comparator (and 1-bit DAC)
- Sensor acts as loop filter
- Or so it seems …

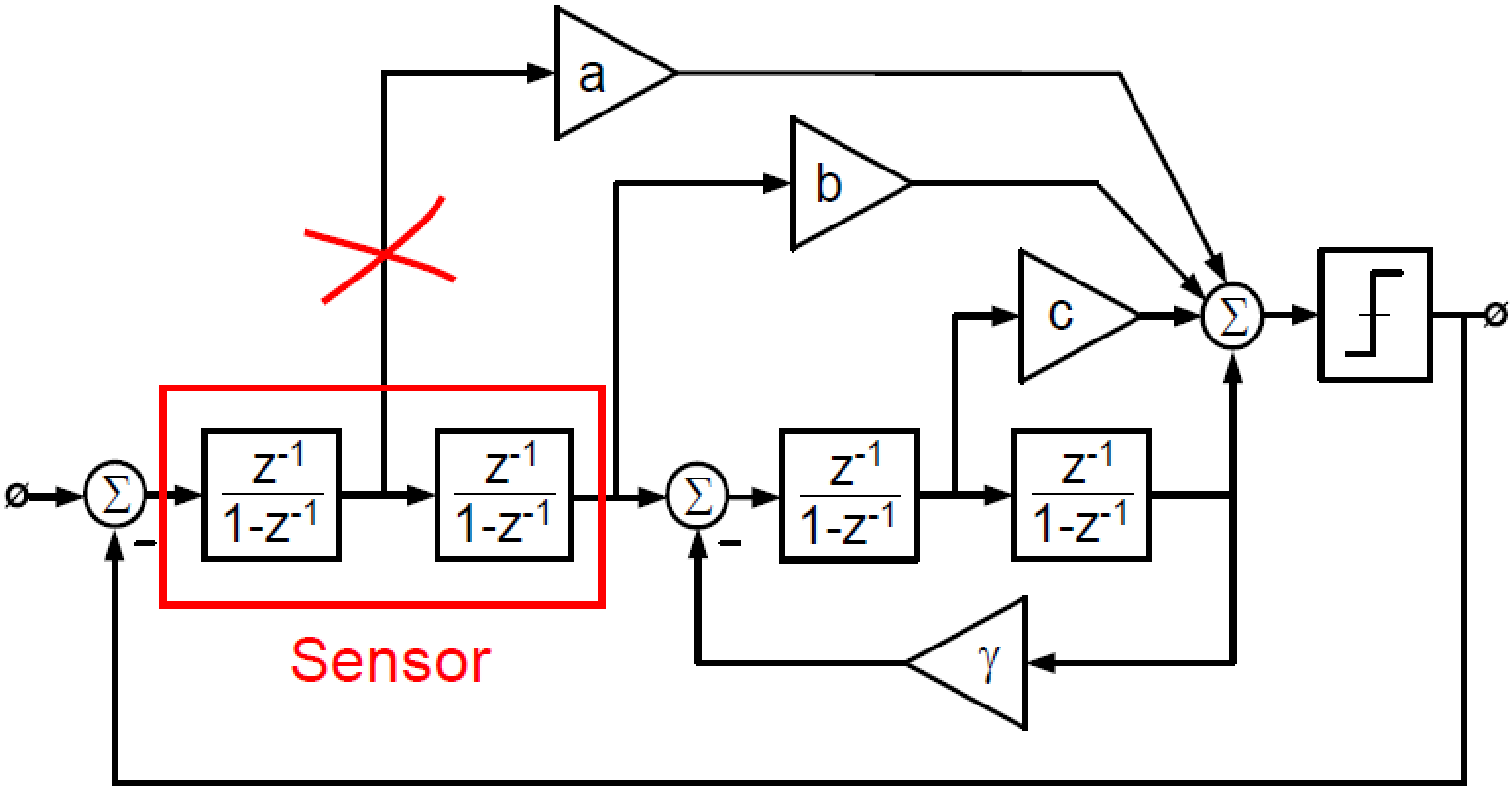
Broad-band Noise



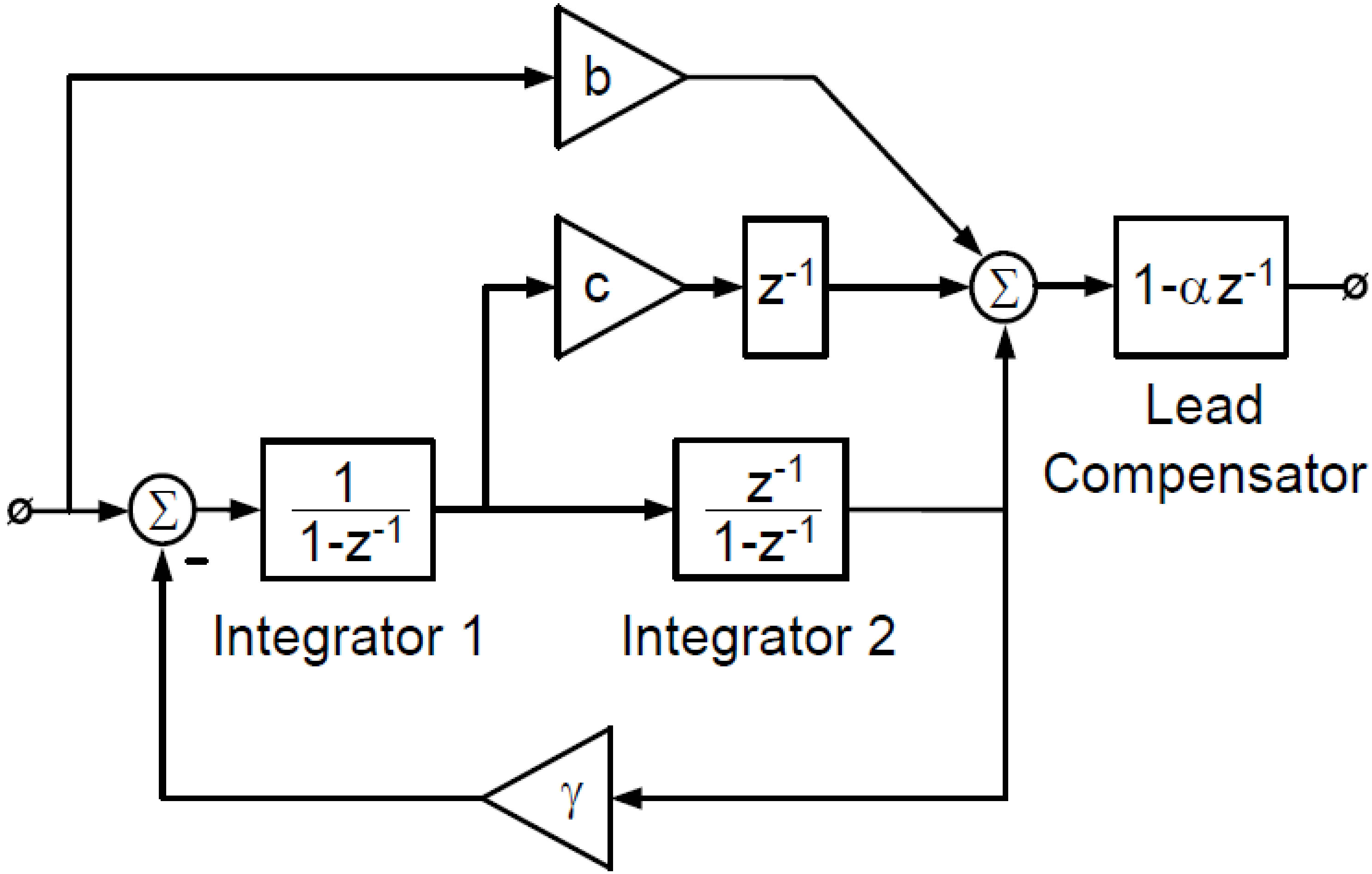




Noise Filter with Feed-forward for Stability



Lead Compensator



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Conclusions

- **Capacitive sensor interfaces can resolve femto-meter displacements**
- **Challenges**
  - Transducer:
    - Parasitic capacitance, resistance
    - Interference → pseudo differential interface
    - Nonlinearity
  - Electrostatic Force-Feedback
    - Scale-factor sensitivity to absolute voltage
    - Stability: 2^{nd} order system, parasitic resonances
    - Sigma-delta ADC: noise enhancement