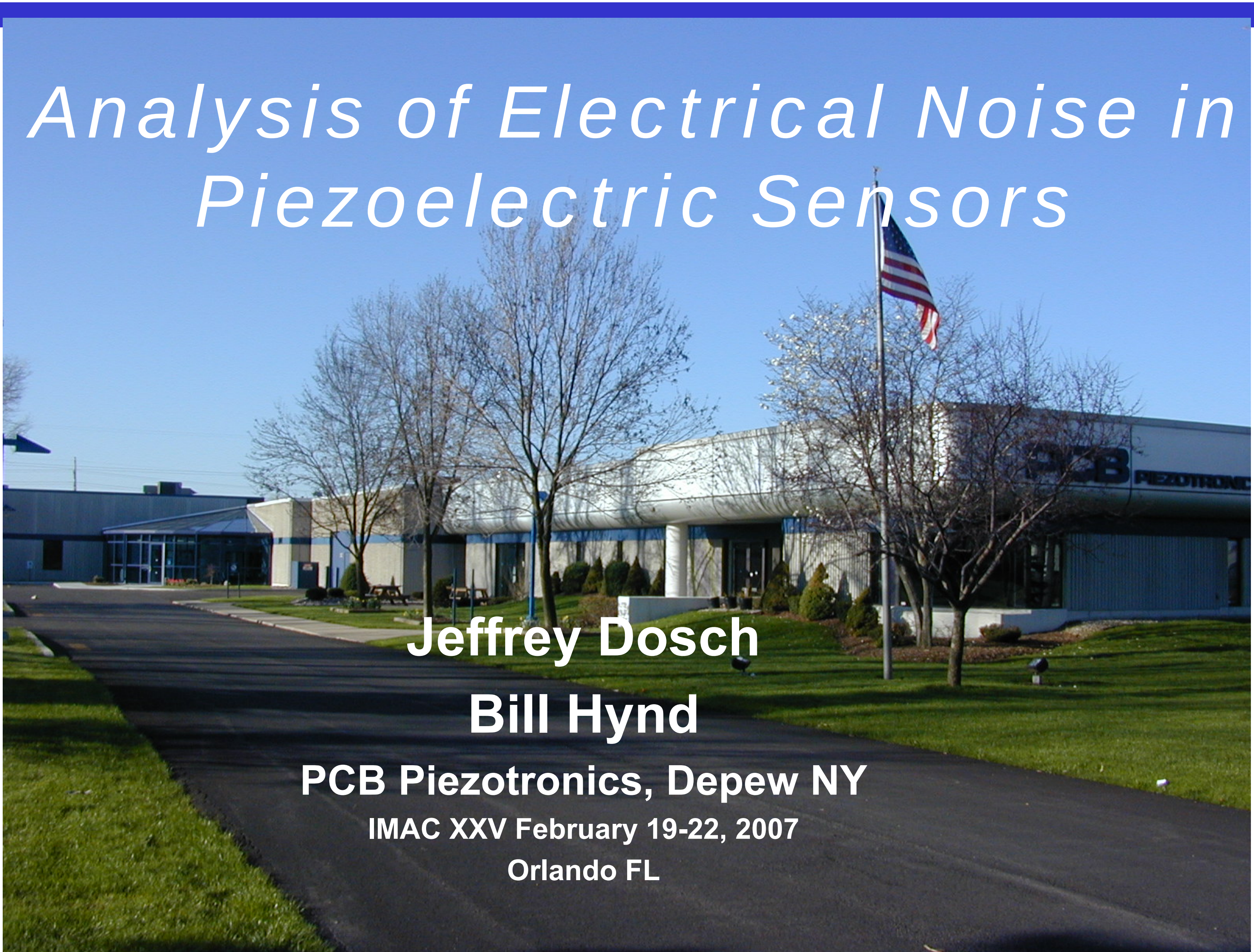
PCB PIEZOTRONICS INC.



Analysis of Electrical Noise in Piezoelectric Sensors

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What is noise?

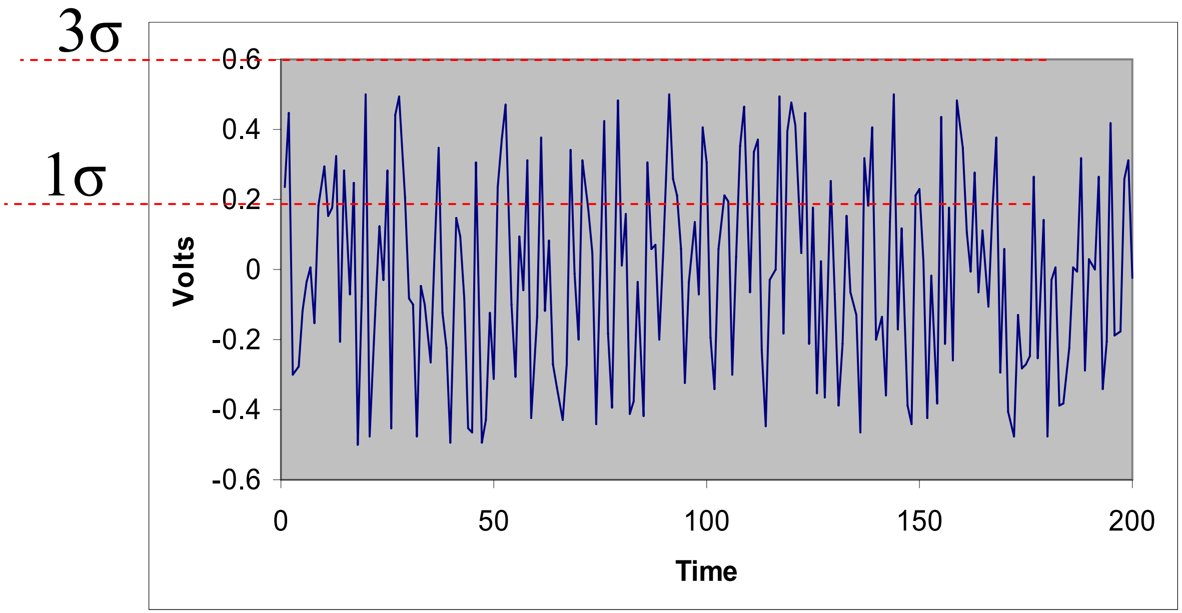
- Noise is any undesired signal.
- Electrical noise is intrinsic to sensor.
  - Noise floor will limit ability to resolve of small signals
- Extrinsic noise. Noise induced because of sensor susceptibility to environment.
  - Thermal transients
  - Base strain
  - Cable strain
  - Magnetic fields
  - Electric fields
  - EMI
  - Cross axis motion
  - Ground loops
  - Channel cross talk
  - Cable triboelectric
  - etc

Outline

- How noise is measured and specified.
- Basic construction of piezoelectric sensors.
- Noise considerations in sensor design.
  - Thermal noise (Resistor)
  - FET noise
  - Internal amplifiers (ICP®)
    - Voltage amplifiers.
    - Charge amplifiers.
  - External charge amplifiers.

Noise measurement

- Noise is a random process.
  - Time domain noise specified by the rms value.
    - Volts rms; g rms; m/s^2 rms
  - In frequency domain noise is specified by power spectral density.
    - V^2/Hz; $V/\sqrt{Hz}$; g^2/Hz; $g/\sqrt{Hz}$

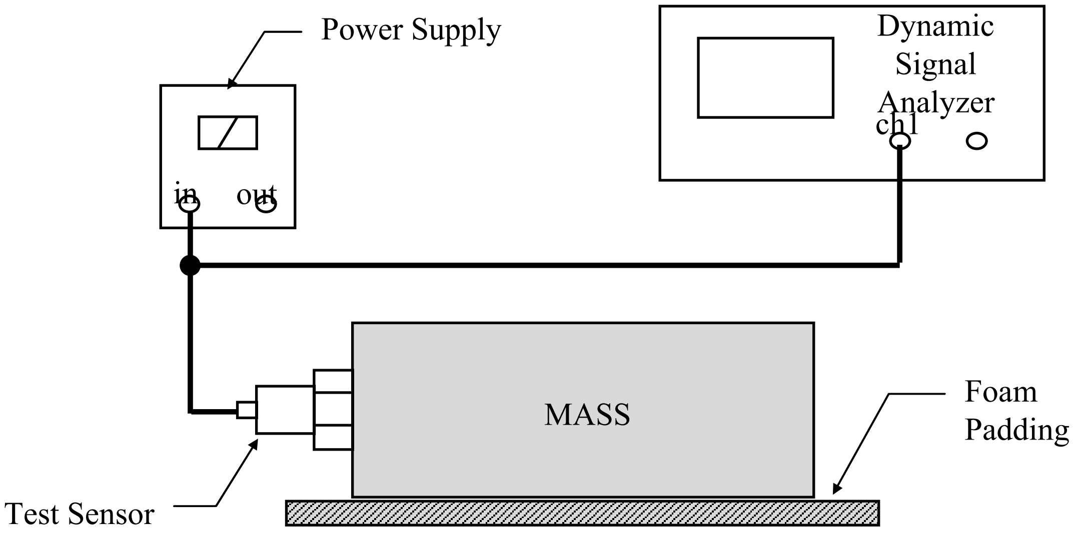


PEAK VALUE

<1σ	68.2% of time
<2σ	95.4% of time
<3σ	99.7% of time

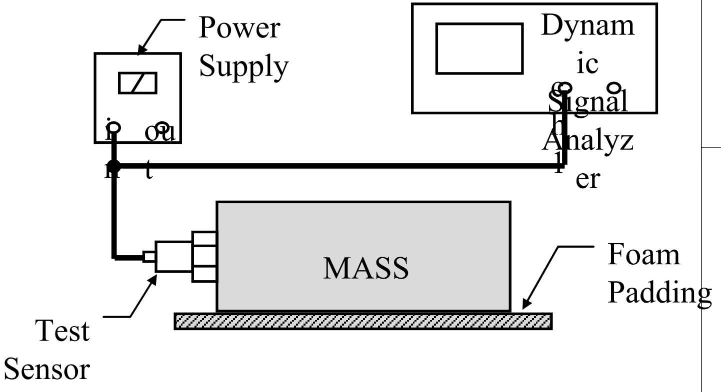
Noise measurement

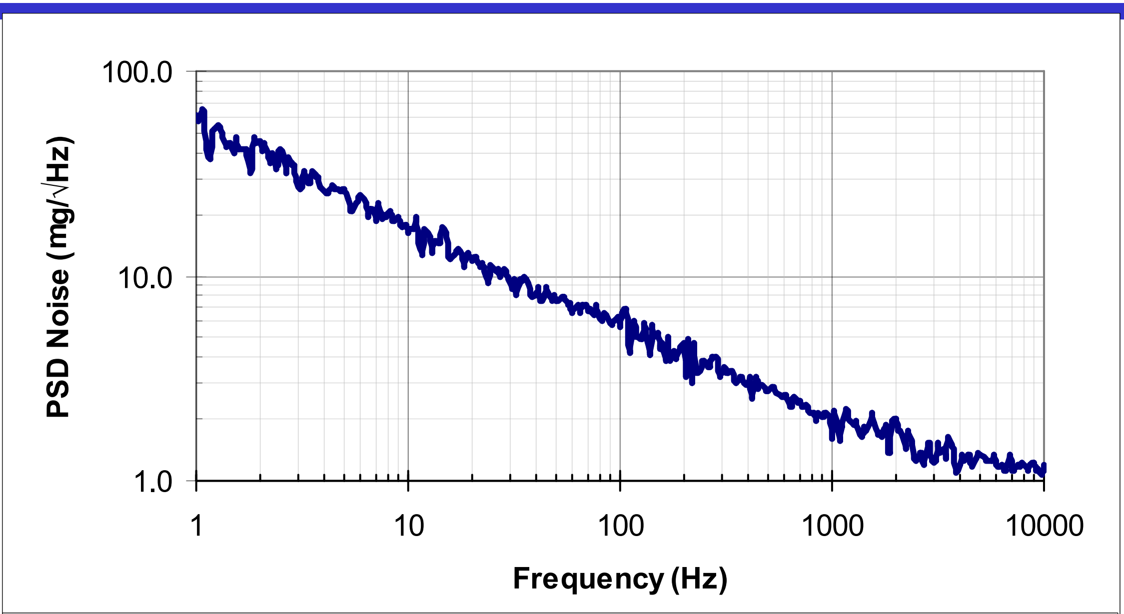
- Mount SUT in quiet environment.
- Spectrum Analyzer to Measure PSD

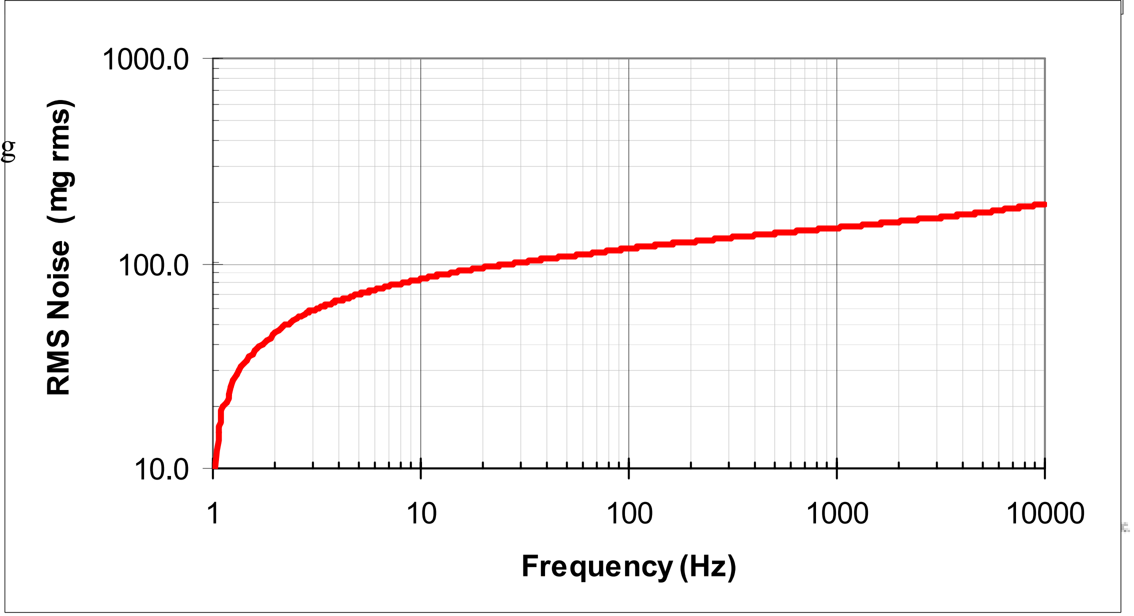


Noise measurement

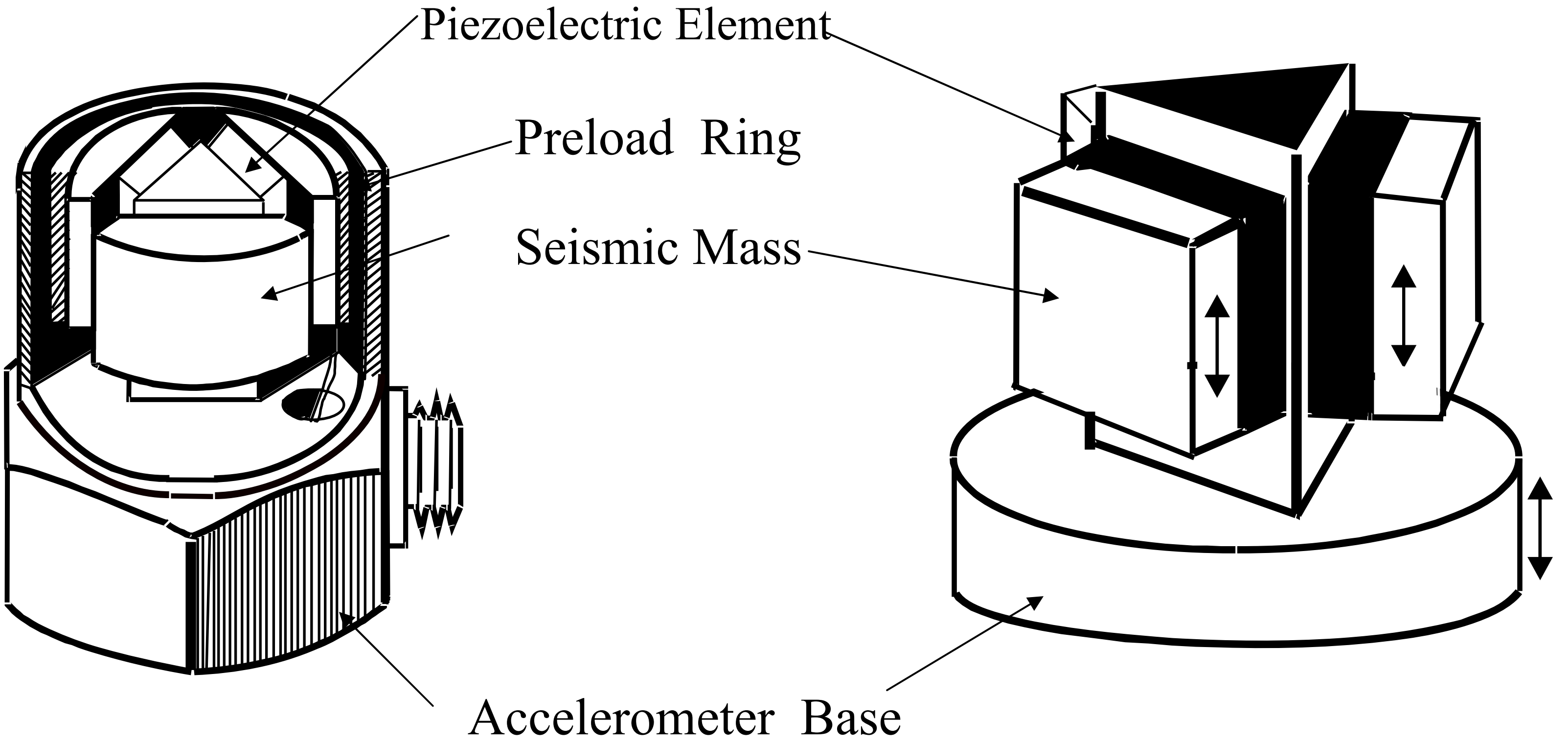
- RMS noise found by integrating PSD.







Accelerometer construction



Piezoelectric Element

Preload Ring

Seismic Mass

Accelerometer Base

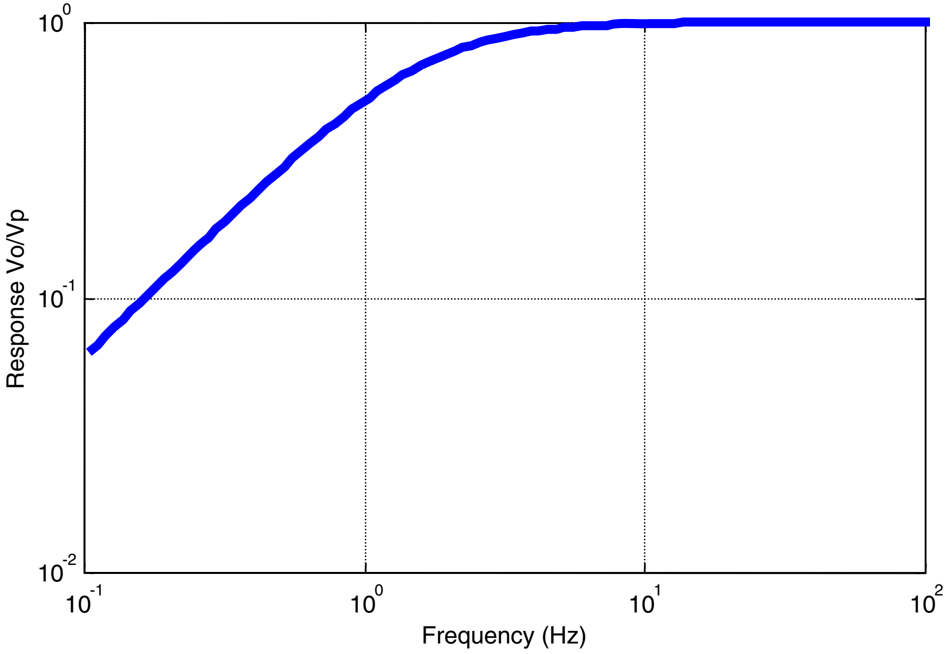
Piezoelectric materials

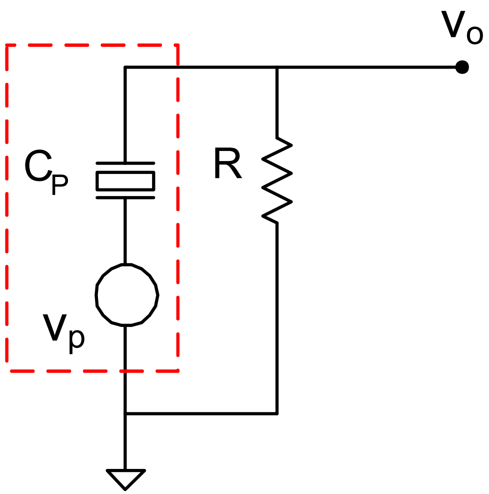
- PZT piezoceramic
  - High charge sensitivity
    - d15 = 580 pC/N (charge constant)
    - g15 = 38 V-m/N (voltage constant)
- Quartz
  - Stable, not pyroelectric
  - Low charge sensitivity, but high voltage sensitivity
    - d26 = 4.6 pC/N (charge constant)
    - g26 = 118 V-m/N (voltage constant)

Time constant

- Piezo modeled as capacitor and voltage source.
- Resistor creates RC filter to attenuate thermal response.

$$\frac{V_o}{V_p} = \frac{RCs}{1+RCs} = \frac{\tau s}{1+\tau s}$$





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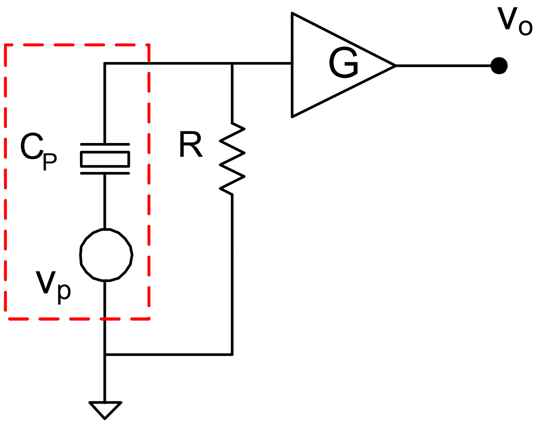
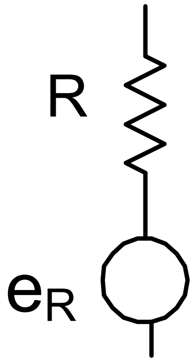
Voltage amplifier

- Amplifies and buffers piezo element voltage.
- Used with quartz sensors.
- Noise from two sources (RSS addition):
  - Resistor (Thermal noise)
  - Amplifier
    - MOSFET transistor



Thermal noise

- Modeled as voltage in series with the resistor.



$$S_{RR} = 4kTR \quad \left[V^2 / Hz\right]$$

- Thermal noise is in proportion to temperature and resistor value.
  - At RT: R=1e9, e_R = 4 μV/ /√Hz; R=1e12, e_R = 0.12 mV/ /√Hz
- Low noise circuits utilize resistors with low excess noise.
  - Excess noise is noise greater than theoretical
  - Excess noise has 1/f spectrum. Is proportional to DC current flow.

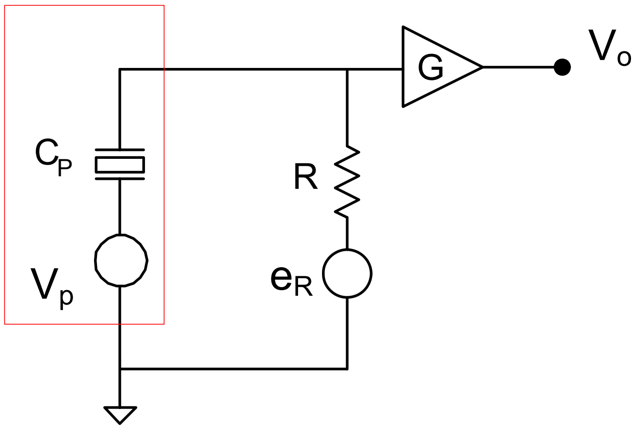
Thermal noise: output referred

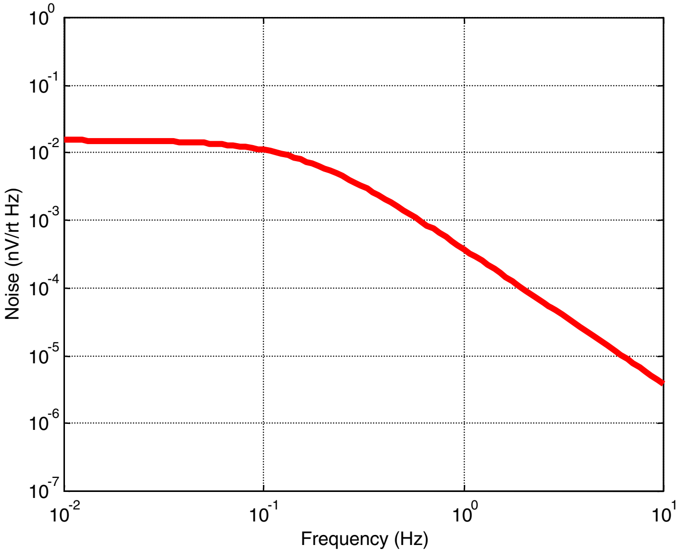
- Transfer function for thermal noise

$$H_R(s) = \frac{V_o}{V_R} = \frac{G}{1 + RC_p s}$$

- Spectral density

$$S_{oo}(\omega) = S_{RR}\left|H_R\right|^2 = \frac{4kTRG^2}{1 + (RC_p)^2\omega^2} = \frac{4kTG^2(\tau / C)}{1 + (\tau)^2\omega^2}$$



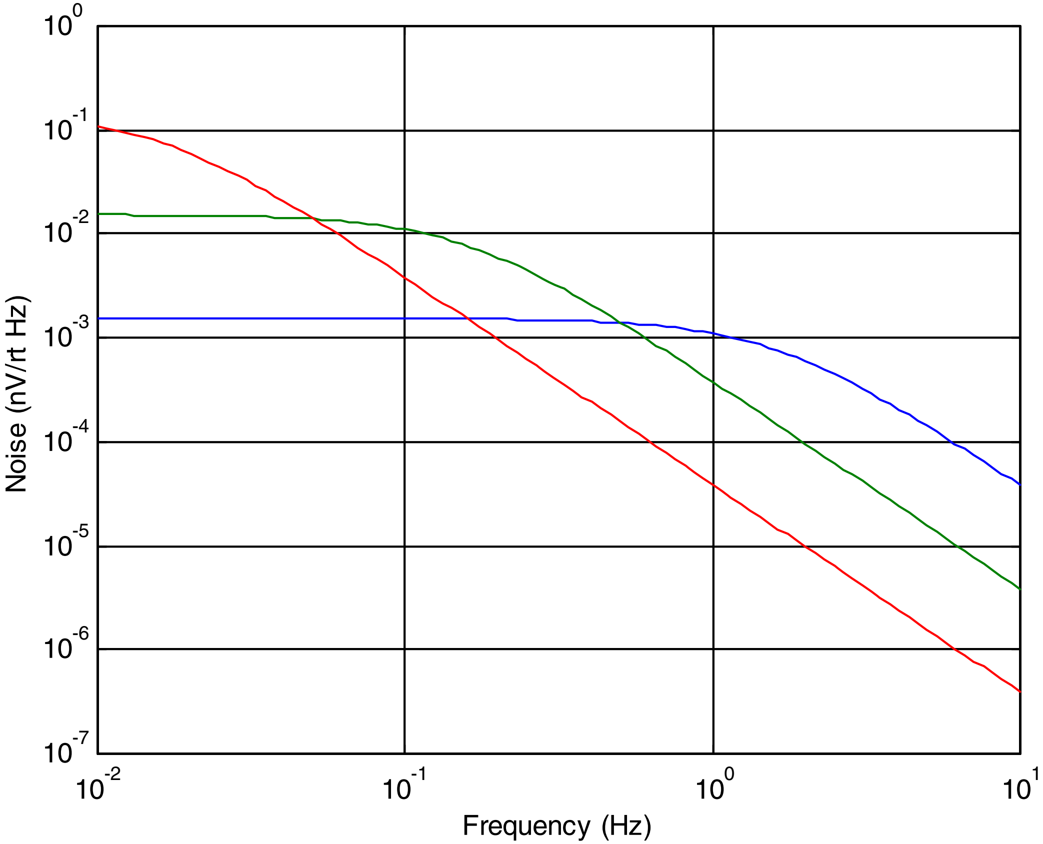


Thermal noise: time constant

- Longer time constant, lower noise

$$\omega >> 1/\tau$$

$$S_{oo}^{1/2}(\omega) = \sqrt{4kT}\,g\,\frac{1}{\omega\sqrt{\tau C}}$$



$$\tau = .1$$

$$\tau = 1$$

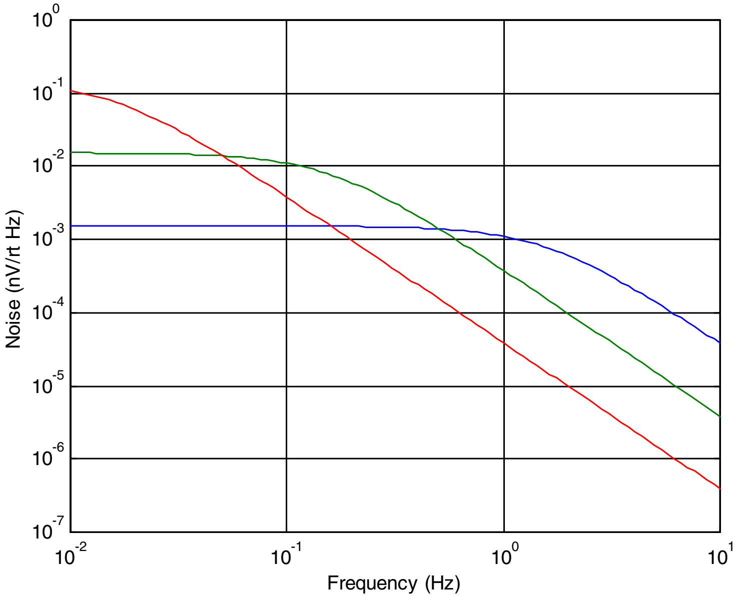
$$\tau = 10$$

Thermal noise RMS

- RMS found by integrating spectral noise:

$$e_n^2 = \int_0^\infty S_{rr}\left|H_R\right|^2 d\omega = kT\,\frac{1}{C} \qquad e_n = \sqrt{kT}\,\frac{1}{\sqrt{C}}$$

- RMS noise depends only on capacitance!
  - Real sensors have finite bandwidth.



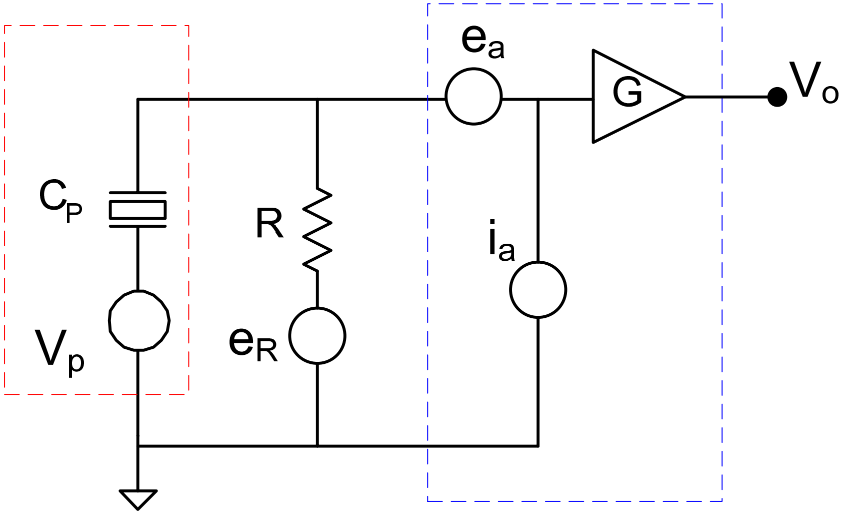
$\tau = .1$

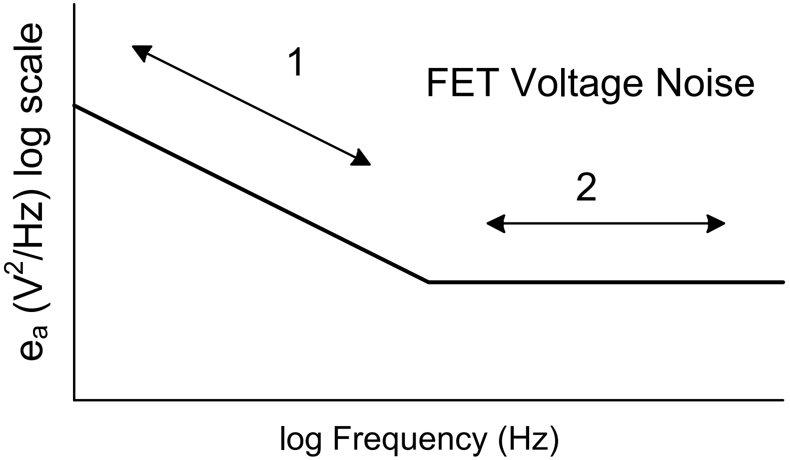
$\tau = 1$

$\tau = 10$

Voltage amp noise

- Model includes MOSFET voltage and current noise.
  - Current noise is small and can generally be ignored
  - FET voltage noise can be measured, or found from specs
  - FET noise is multiplied by amp gain

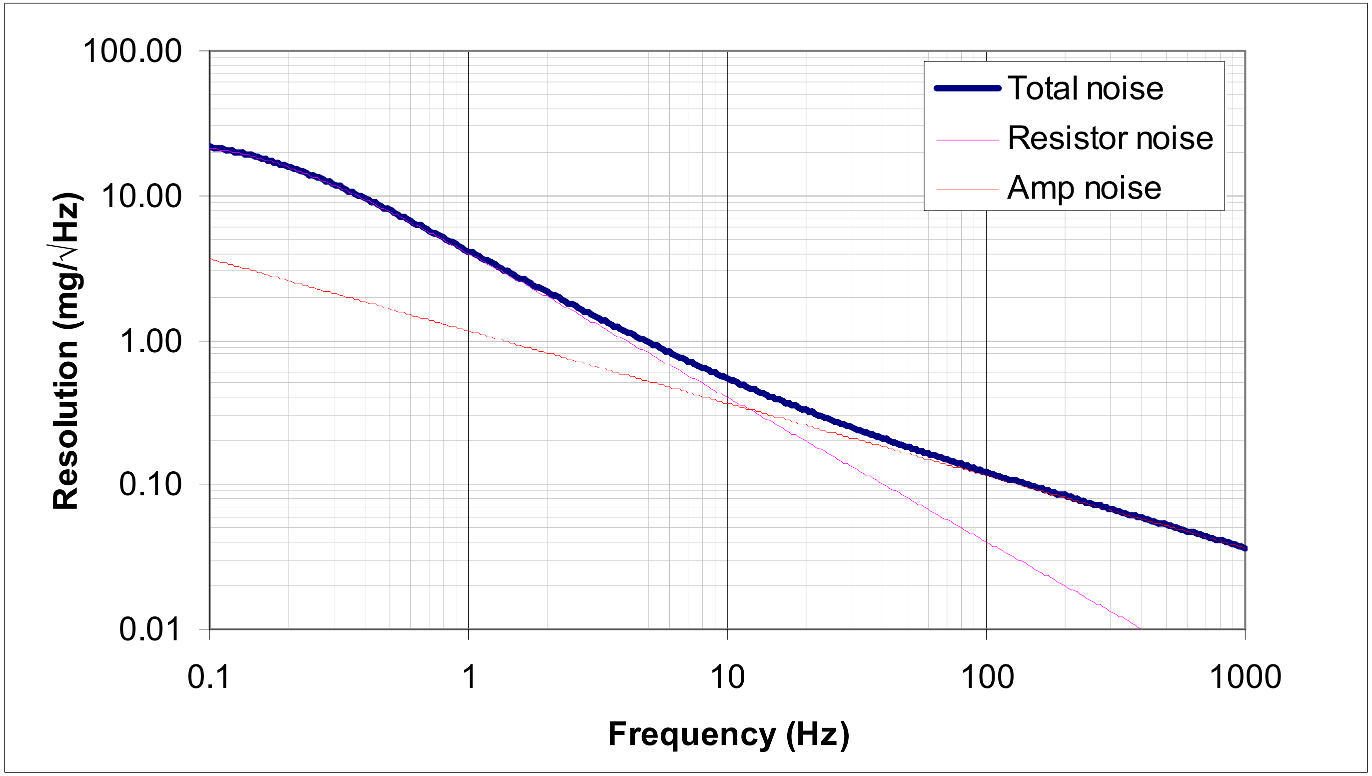




Voltage amp noise

- Total noise found by RSS of resistor and FET noise.

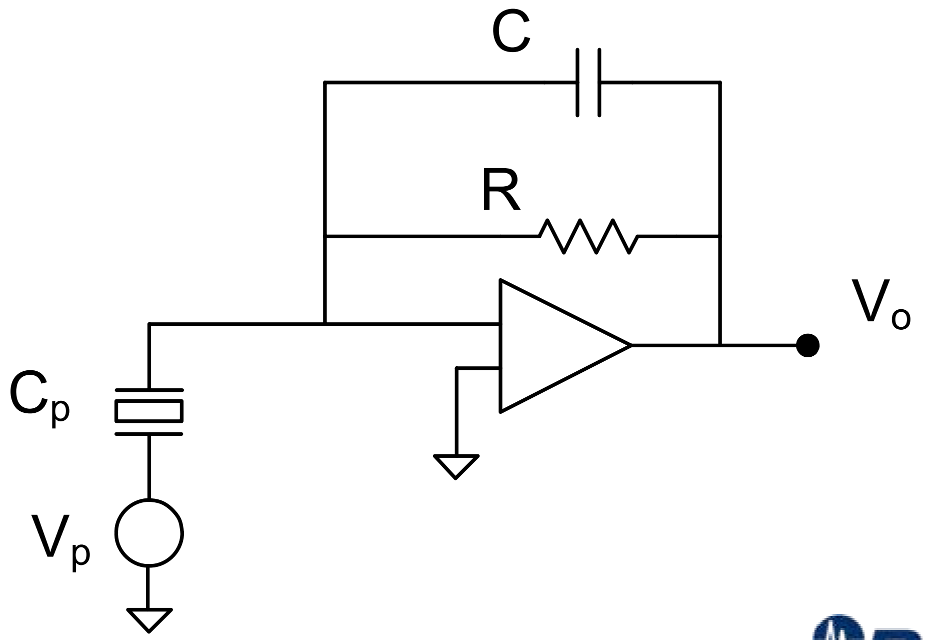
QUARTZ ACCEL
Tau = 1 sec
R = 2E11
Sens 10 mV/g
Gain = 2.1



Charge amp

- Output is in proportion charge.
- Gain is:

$$G = \frac{C_p}{C} \qquad V_o = GV_p$$



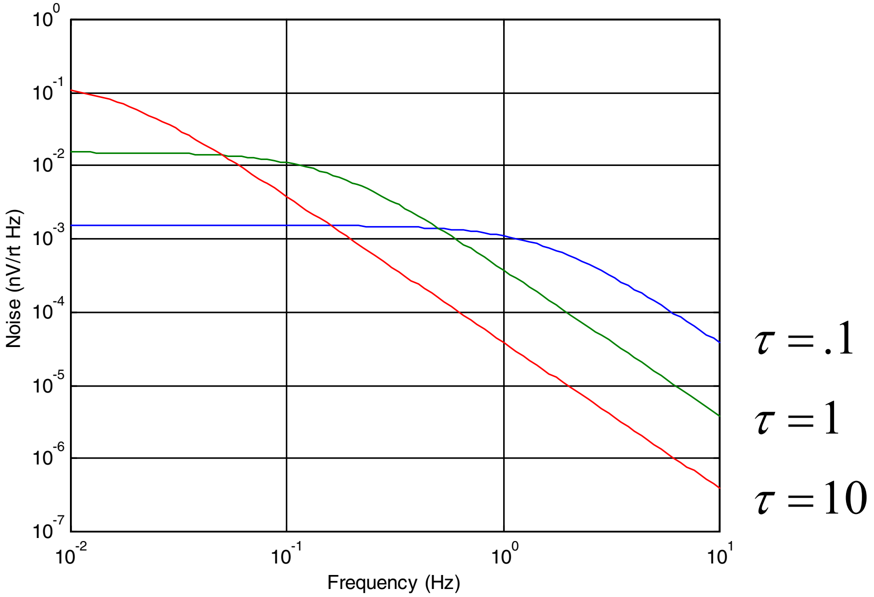
$$V_o = \frac{Q_p}{C}$$

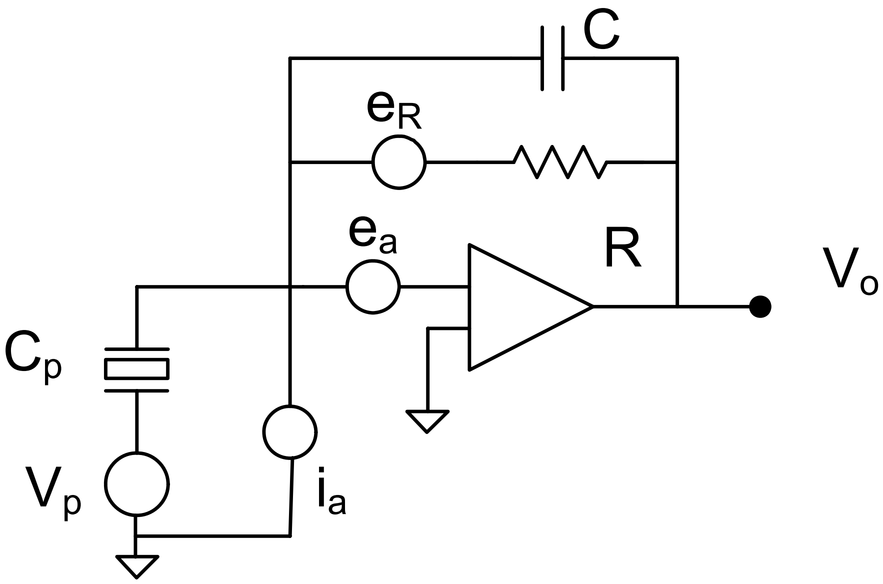
Charge amp noise

- Thermal (resistor) noise is same as voltage amp case.
- Except, noise is independent of gain.

$$\omega >> 1/\tau$$

$$S_{pp}^{1/2}(\omega)=\sqrt{4kT}\,\frac{1}{\omega\sqrt{\tau C}}$$





Charge amp noise

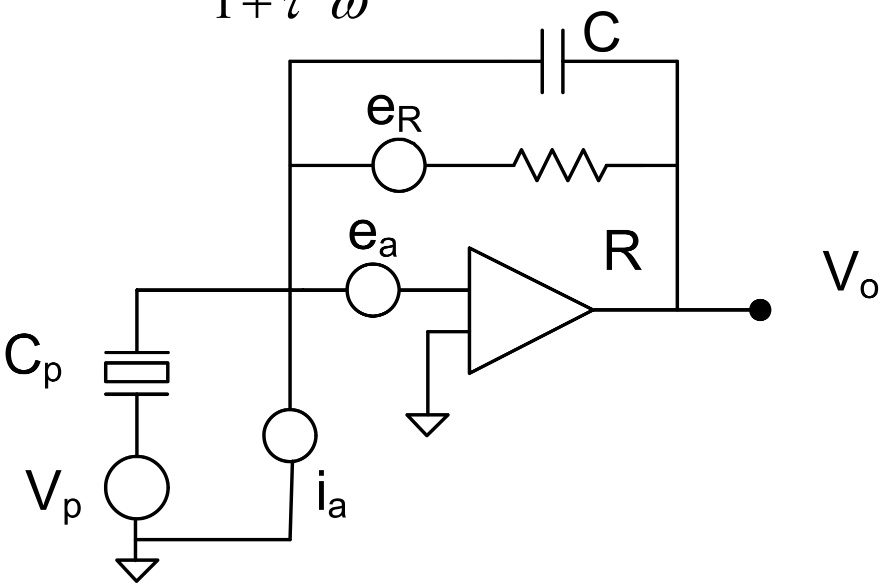
- FET Current noise is usually small and can be ignored.
- FET voltage noise transfers as

$$S_{pp} = S_{aa}\left|H_a\right|^2 = \frac{V_o}{V_a} = S_{aa}\left|\frac{\tau(G+1)j\omega+1}{1+\tau j\omega}\right|^2 = S_{aa}\frac{\tau^2(G+1)^2\omega^2+1}{1+\tau^2\omega^2}$$

- For $\omega >> 1/\tau$ reduces to:

$$S_{oo}^{1/2} = S_{aa}^{1/2}(G+1)$$

$$G = \frac{C_p}{C}$$

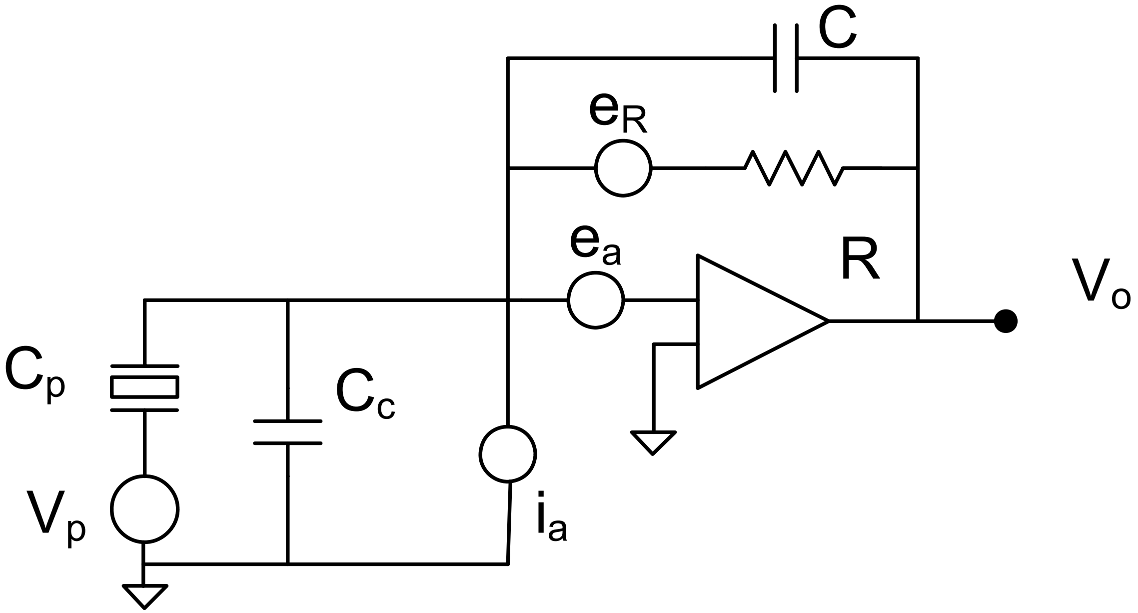


External charge amp

- Added source capacitance due to cable.
  - Amp noise gain increased

$$S_{pp}^{1/2} = S_{aa}^{1/2}(G+1)$$

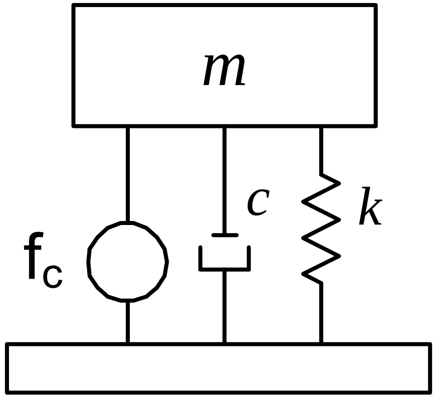
$$G = \frac{C_p + C_c}{C}$$



Thermal noise

- Thermal noise force in mechanical element.
- Noise force generated from damping and temperature.
- Noise is:

$$resolution = \sqrt{4k_B T}\sqrt{\frac{2\zeta\omega_n}{m}} \qquad [\mathrm{m/s^2/\sqrt{Hz}}]$$



- Not significant in piezoelectric sensors.
- Thermal noise is a limit to miniaturization.

Noise example: 333B30

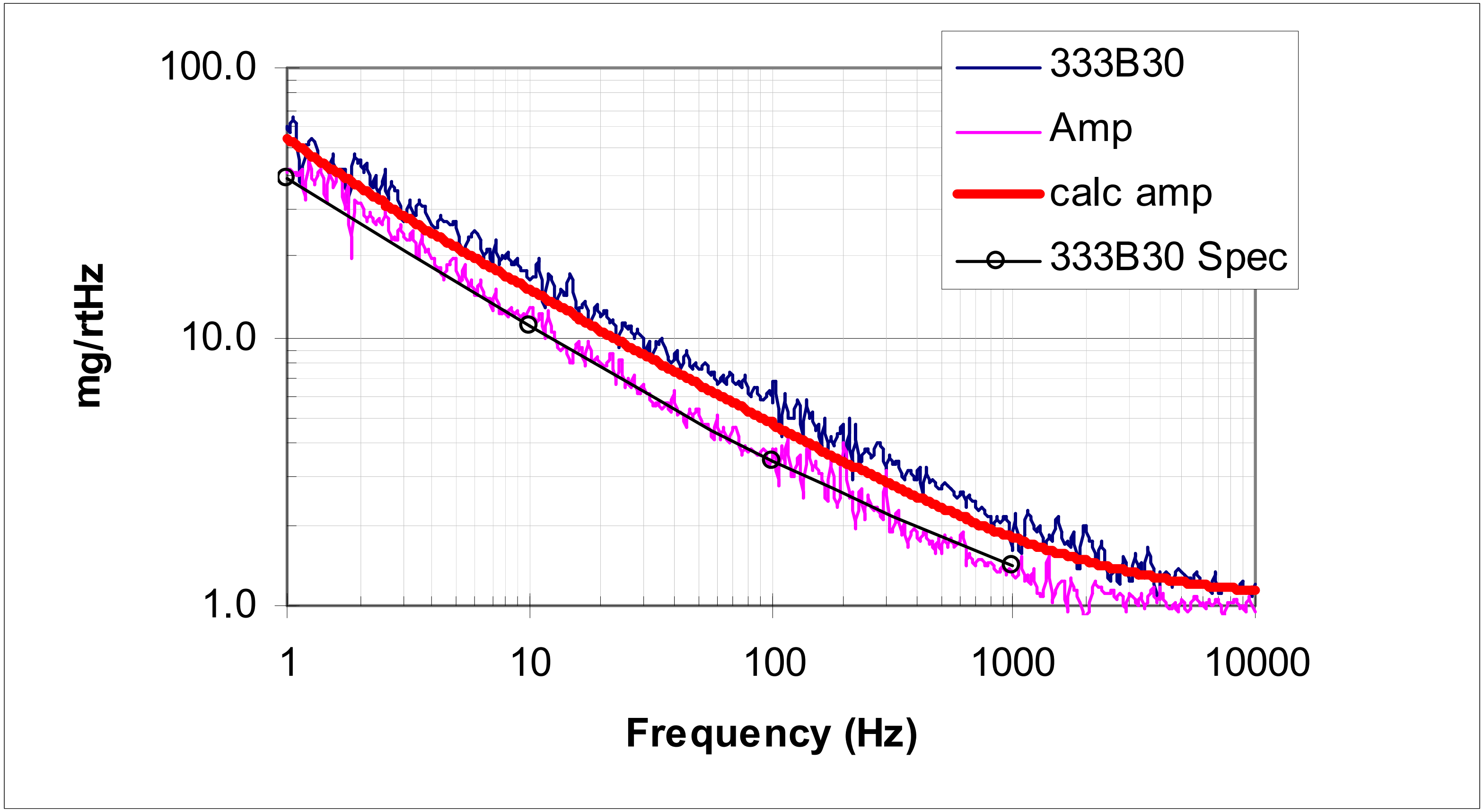
- Design specs

Cp = 690 pF
Cf = 50 pF
Amp Noise Gain = (1+690/50) = 14.8
Time constant = 1-3 seconds

- High gain and long time constant. Would expect that amplifier noise would dominate.

Design Example: 333B30

- Reasonable correlation between calculation and measurement.



Design example: 333B30

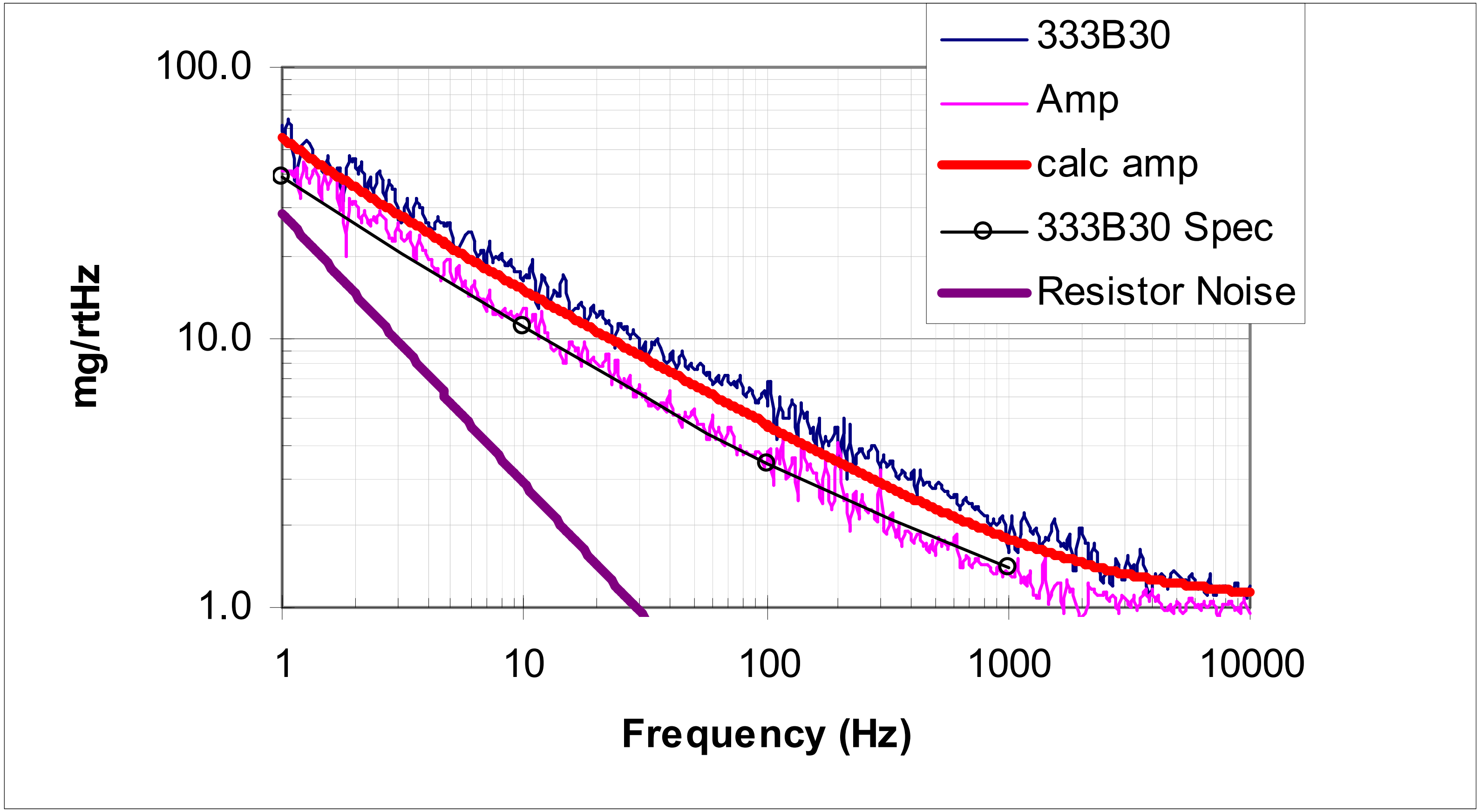
- Design specs

Cp = 690 pF
Cf = 50 pF
Amp Noise Gain = (1+690/50) = 14.8
Time constant = 1-3 seconds
Sensitivity = 100 mV/g

- High gain and long time constant. Would expect that amplifier noise would dominate.

Design Example: 333B30

- Resistor noise has no influence 1Hz to 10kHz



333B30 damping noise

- Design specs

$$\begin{aligned}&Q = 50\\&\text{Resonance} = 44\text{kHz}\\&\text{Mass} = 0.7\text{ grams}\end{aligned}$$

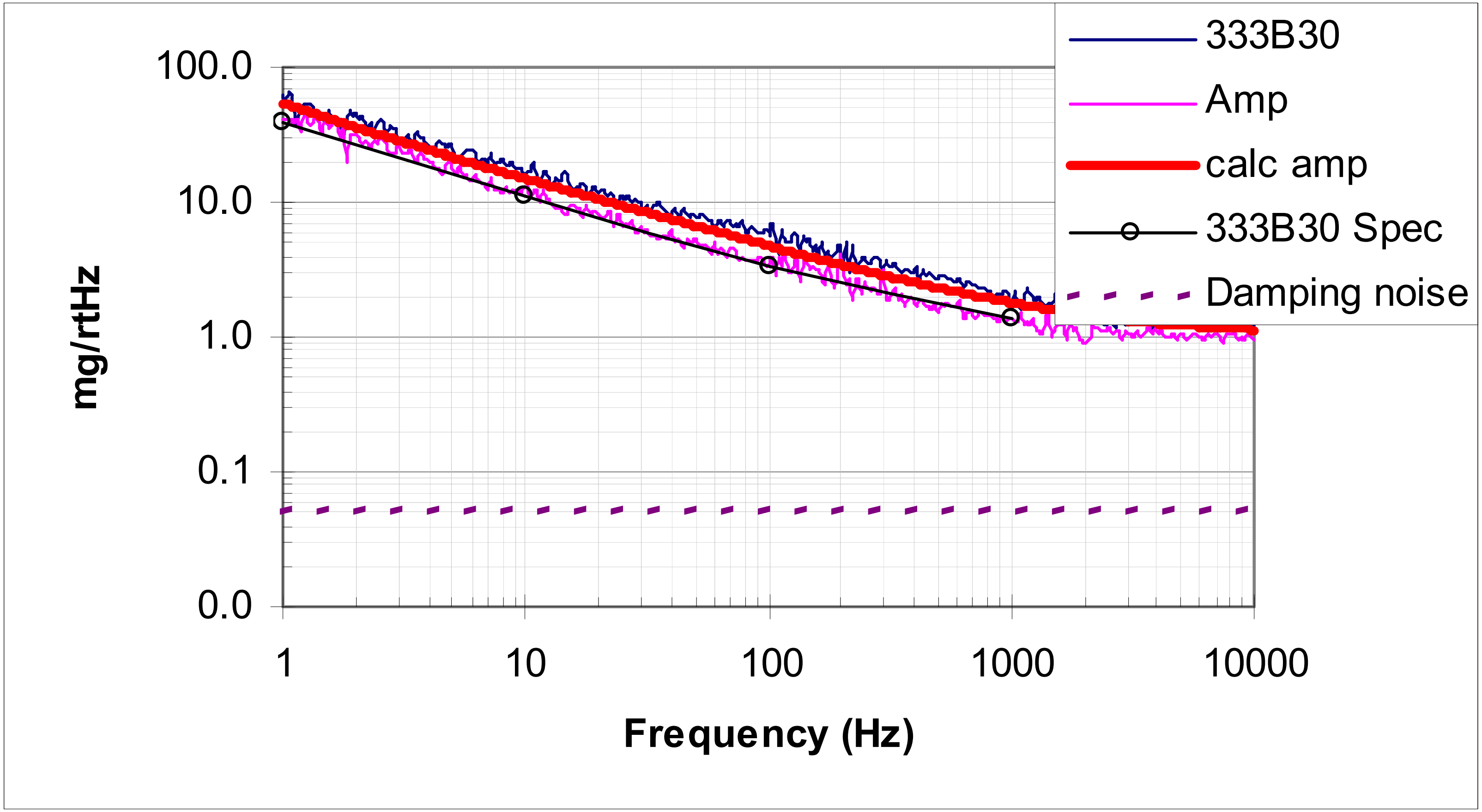
- Resolution

$$resolution = \sqrt{4k_BT}\sqrt{\frac{\omega_n}{Qm}}$$

- Large Q, large mass, high frequency. Expect low damping noise floor.

333B30 Damping noise

- Mechanical damping does not contribute to noise.



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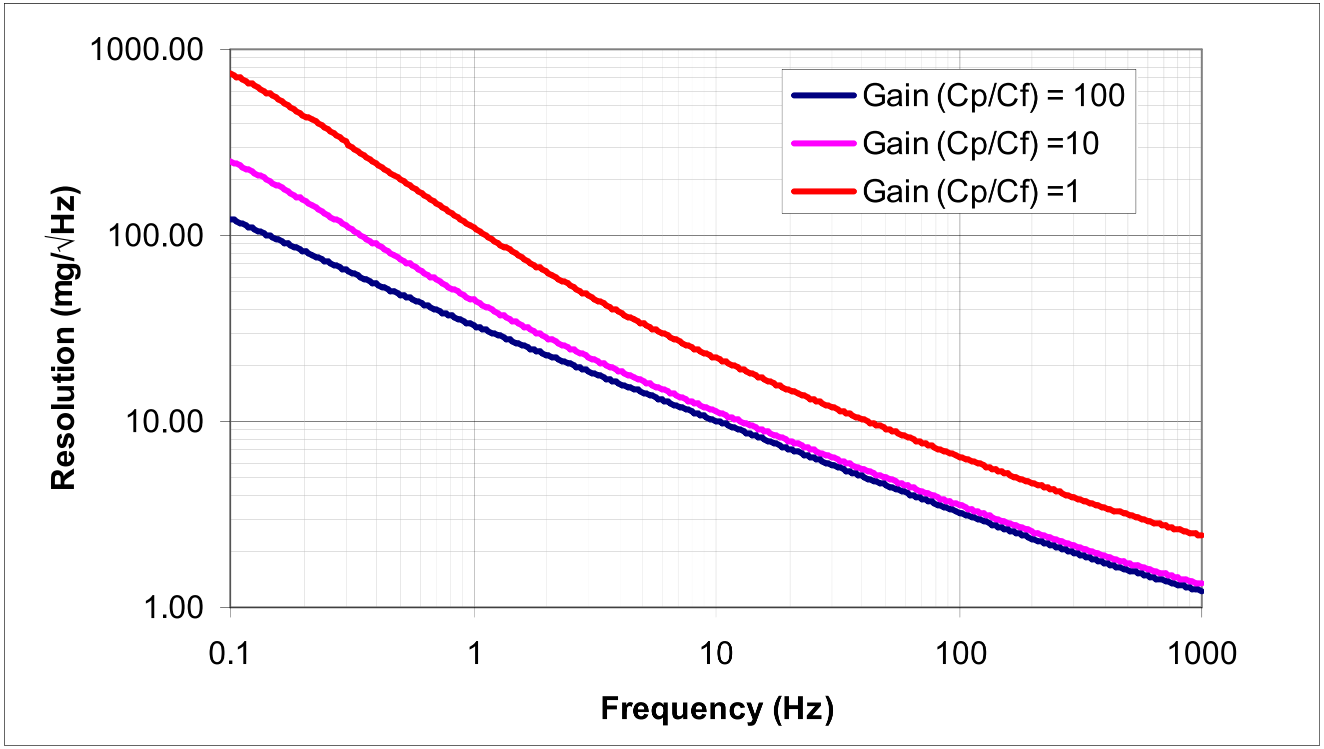
333B30: Design trade-offs

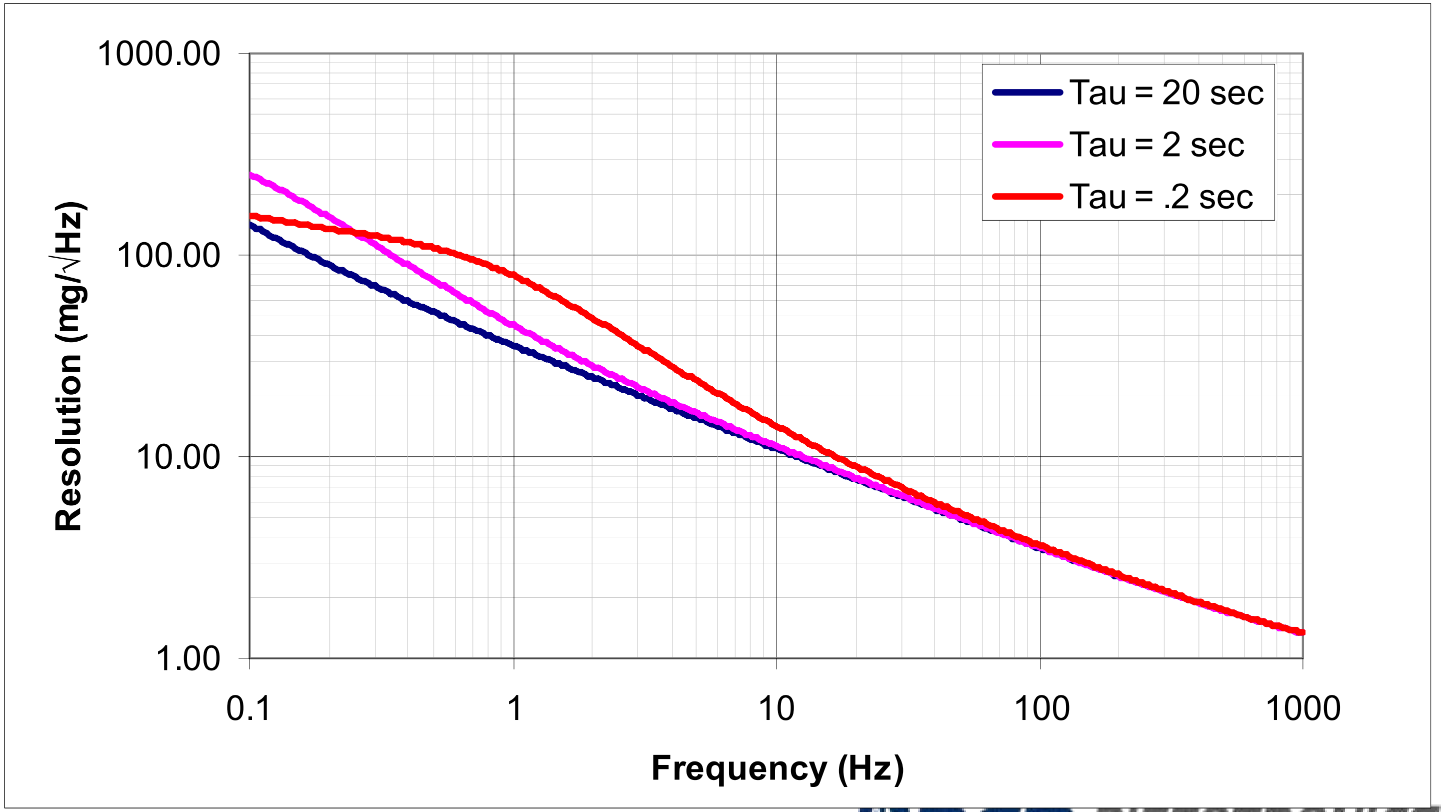
- Increasing charge amp gain improves noise floor.
  - Gain multiplies signal + amp noise. No effect on R noise

(100 mV/g at Gain = 100)



333B30: Design trade-offs

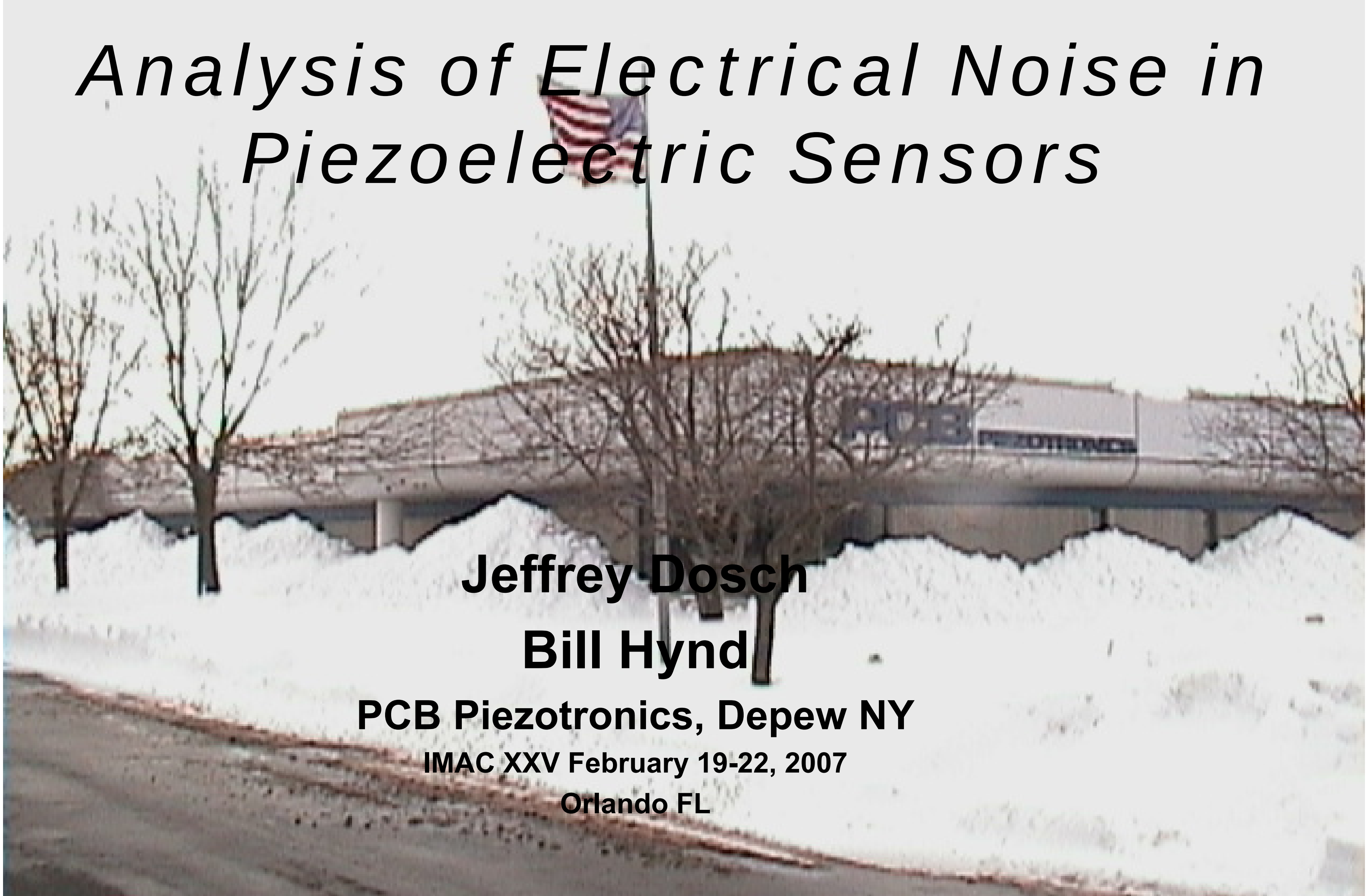
- Longer time constant improves noise floor (0.5-10Hz).
  - Higher resistance, but longer time constant “pushes” noise out of band to low frequency.



Summary

- Thermal (resistor) noise dominates low frequency.
- Amp noise dominates at high frequency.
- Design trade-offs in charge amps:
  - Higher gain usually improves resolution.
  - Longer time constant usually helps low frequency resolution.

Analysis of Electrical Noise in Piezoelectric Sensors



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