Accelerometer Design Example

Analog Devices XL-05/50

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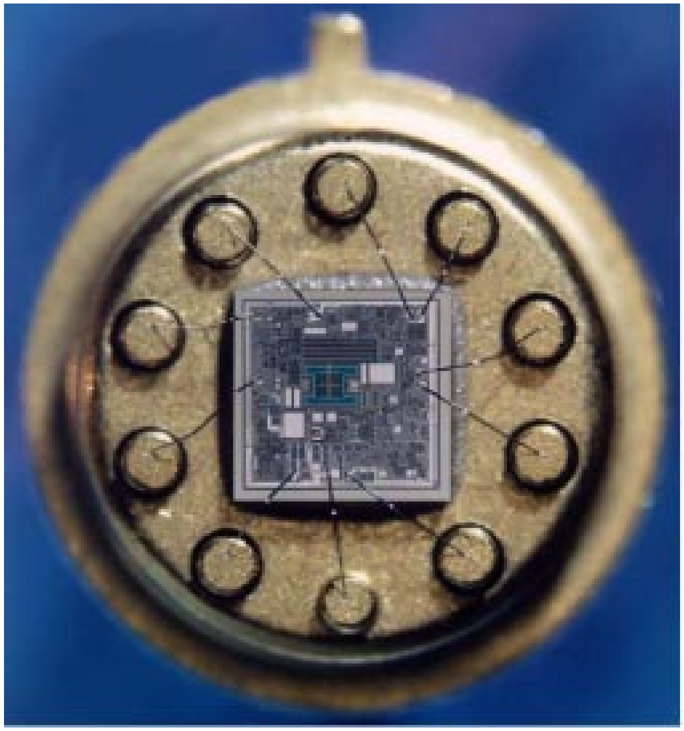
Outline



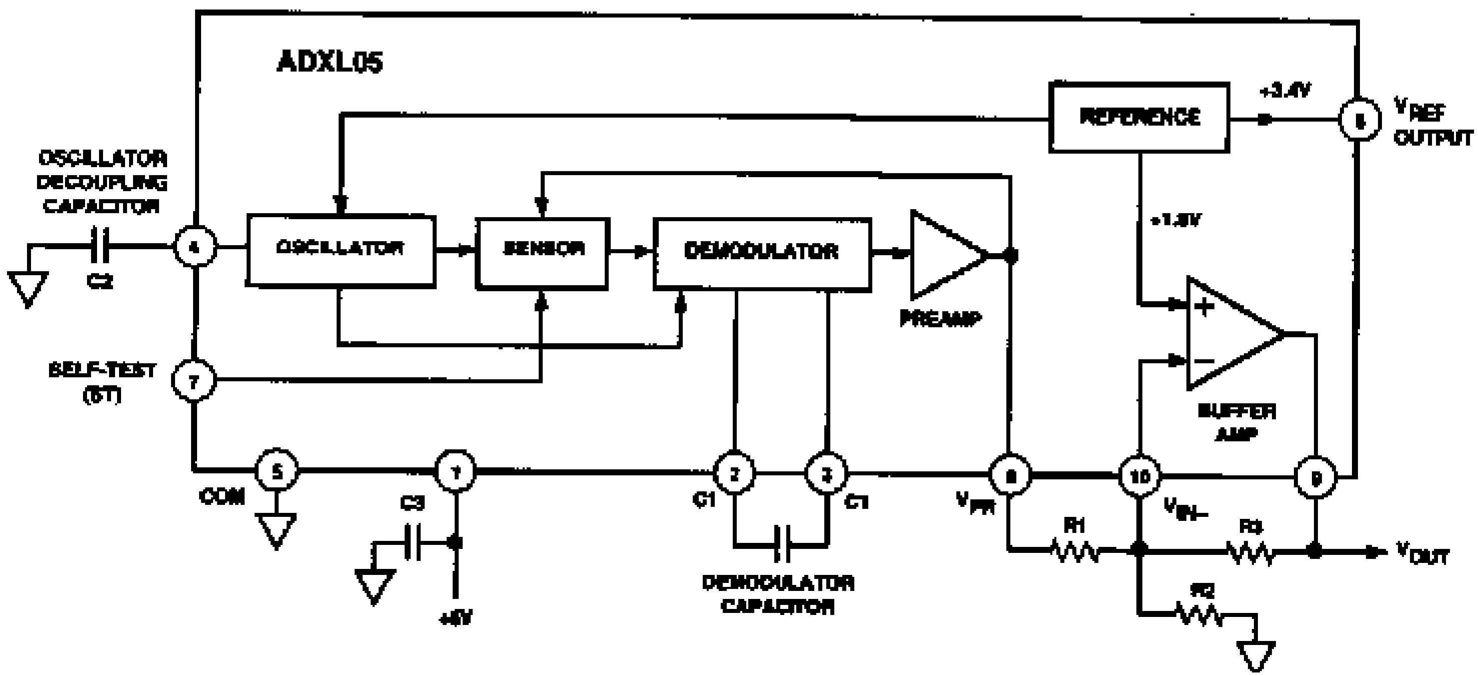
Ref: Analog Devices ADXL-50

- specifications
- system diagram
- sense element
- force-feedback
- resolution

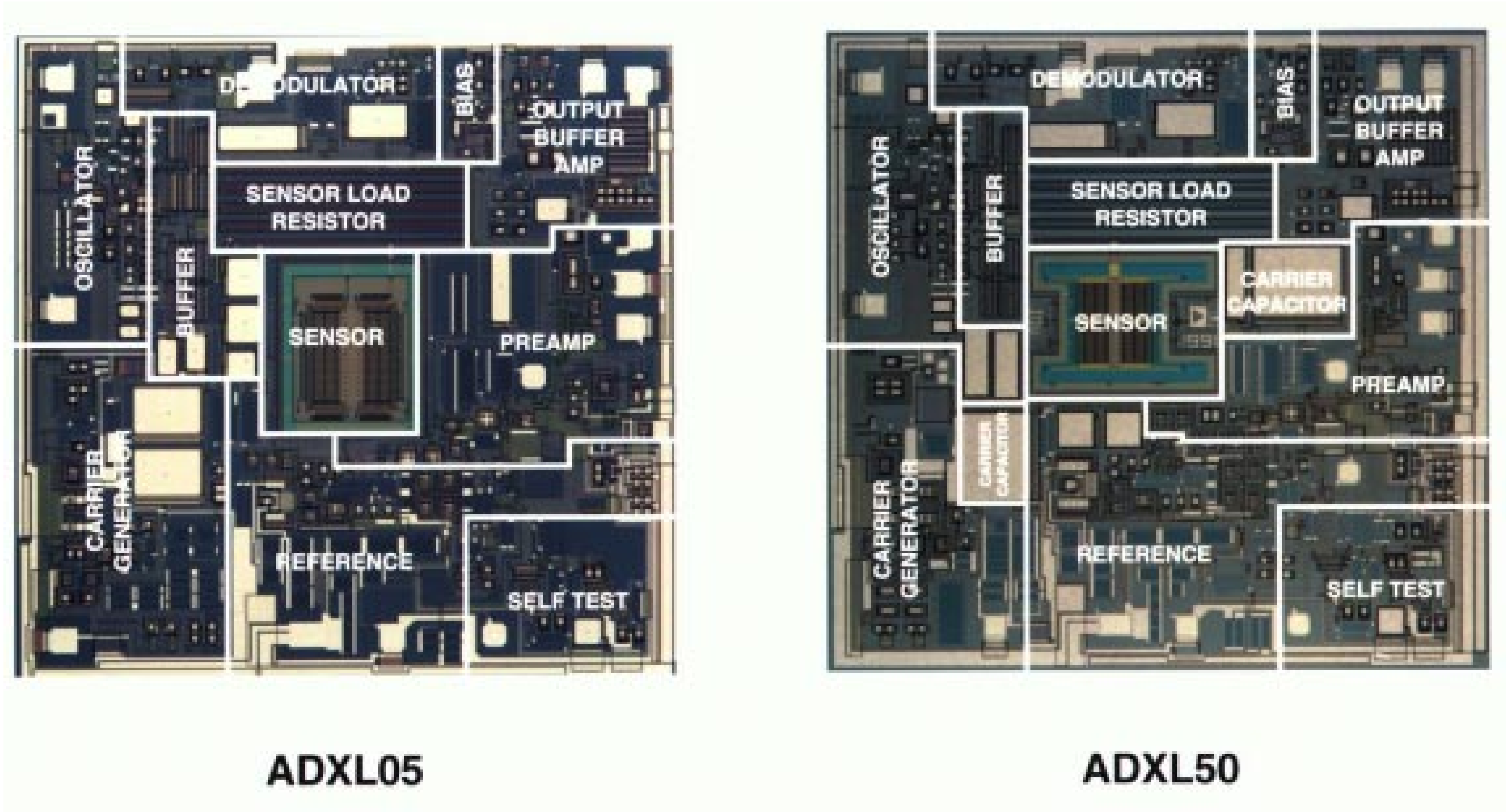
XL05 Specifications

• full scale	$\pm 1 \ldots 5\ g$
• sensitivity	200 mV/g … 1 V/g
• resolution	5 milli-g in 100 Hz (1 g = 9.8 m/s^2)
• noise floor	500 μg/rt-Hz
• bandwidth	1.6 … 4 kHz
• resonance	12 kHz
• linearity	0.2 % of full scale
• off-axis sensitivity	± 2 %
• alignment error	$\pm 1^o$
• supply	5 V, 8 mA

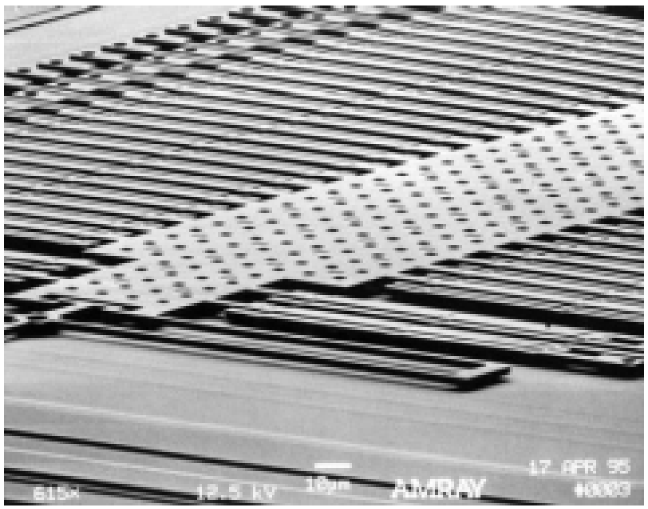
Functional Block Diagram



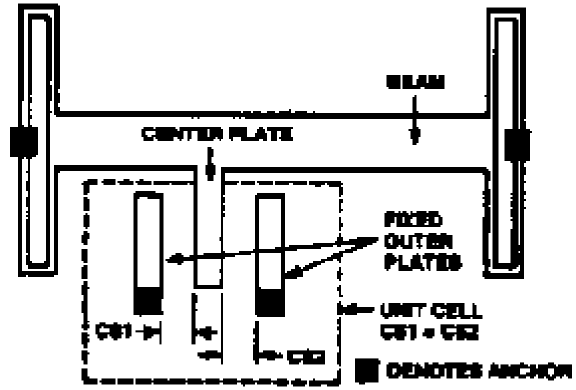
Layout

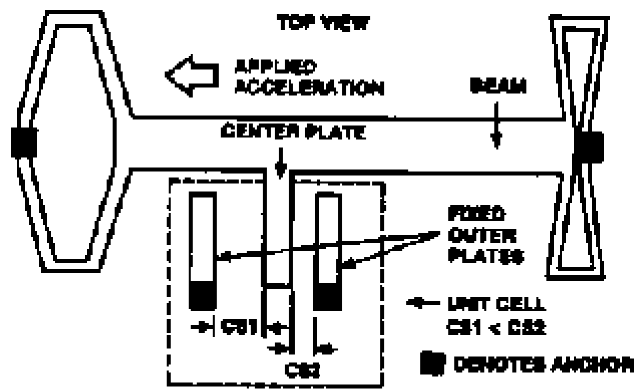

DEMODULATOR
BIAS
OUTPUT
BUFFER
AMP
OSCILLATOR
SENSOR LOAD
RESISTOR
BUFFER
SENSOR
PREAMP
CARRIER
GENERATOR
REFERENCE
SELF TEST
ADXL05
DEMODULATOR
BIAS
OUTPUT
BUFFER
AMP
OSCILLATOR
BUFFER
SENSOR LOAD
RESISTOR
CARRIER
CAPACITOR
SENSOR
PREAMP
CARRIER
CAPACITOR
CARRIER
GENERATOR
REFERENCE
SELF TEST
ADXL50

Sense Element



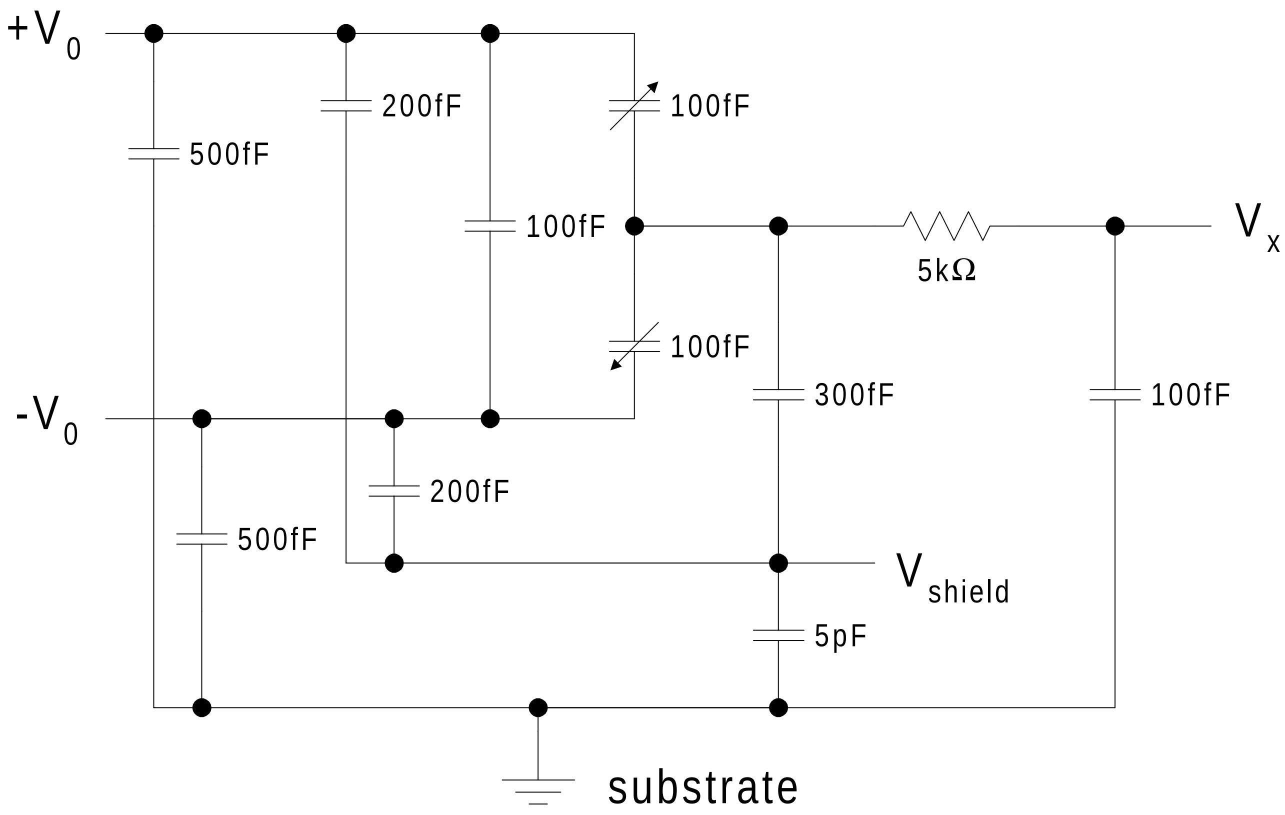
ADXL 05 proof mass.





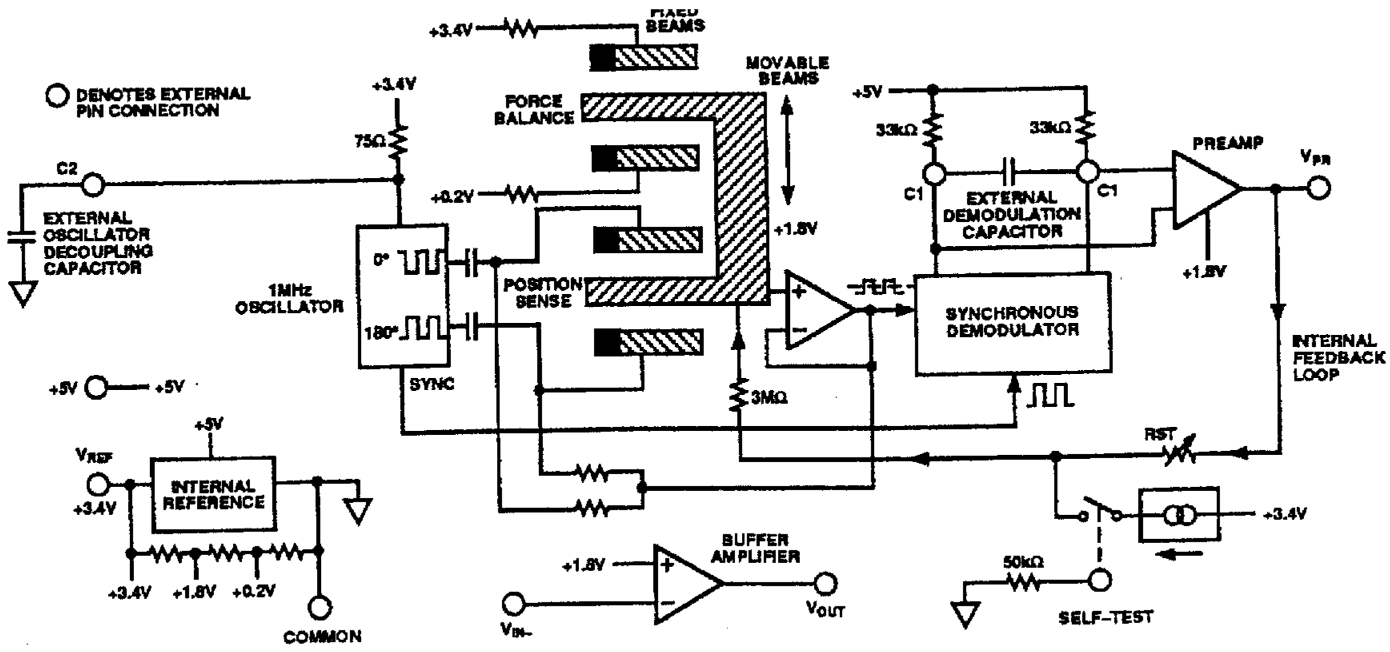
Electrical Interface

(capacitor values estimated)



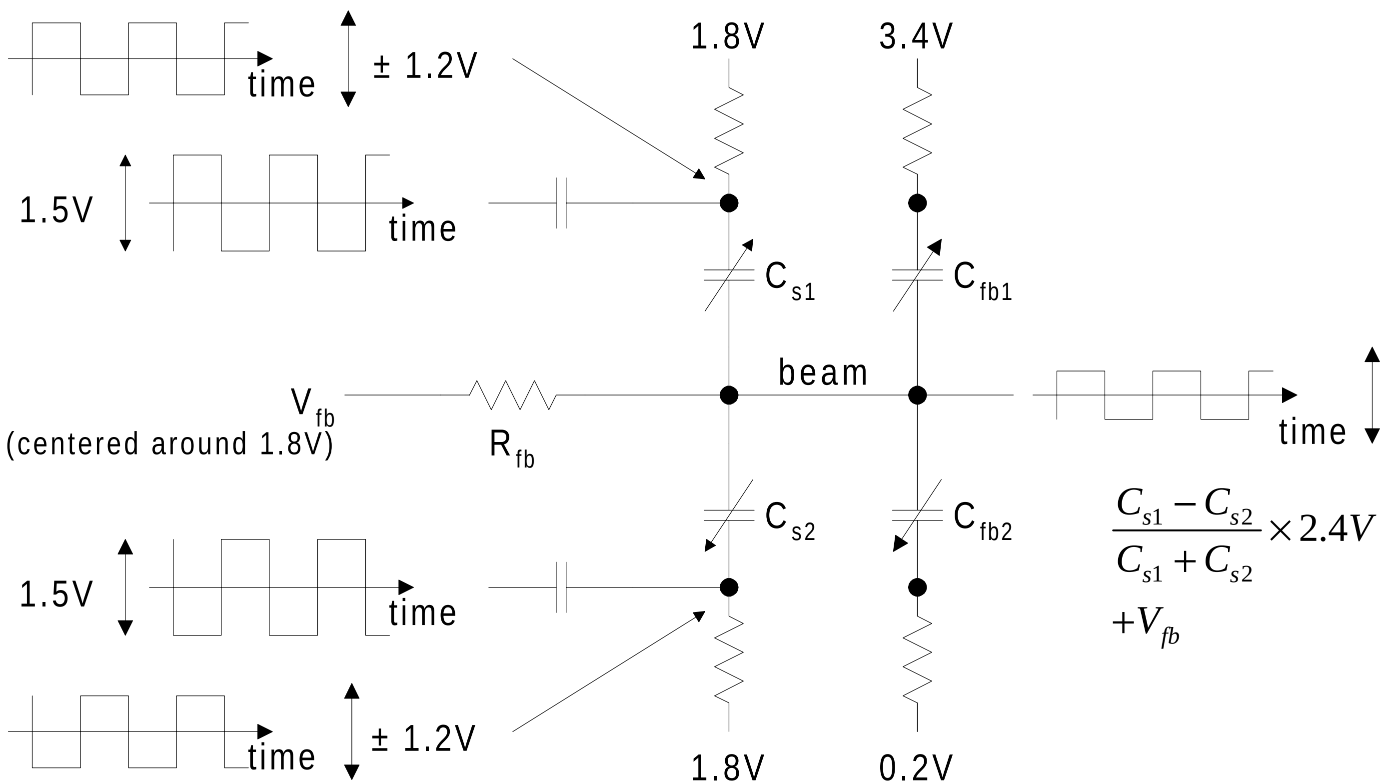
Electrical Block Diagram

XL-05



Capacitive Interface

XL-05

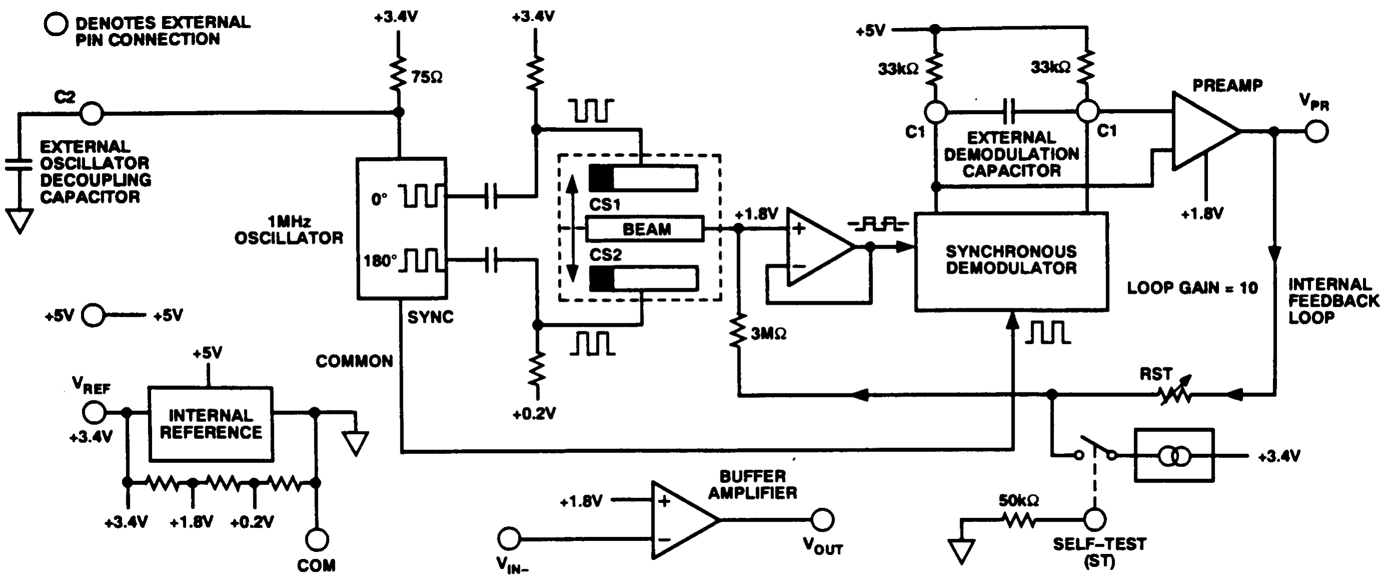


$$\frac{C_{s1} - C_{s2}}{C_{s1} + C_{s2}} \times 2.4V$$ modulated

$+V_{fb}$ DC offset

Electrical Block Diagram

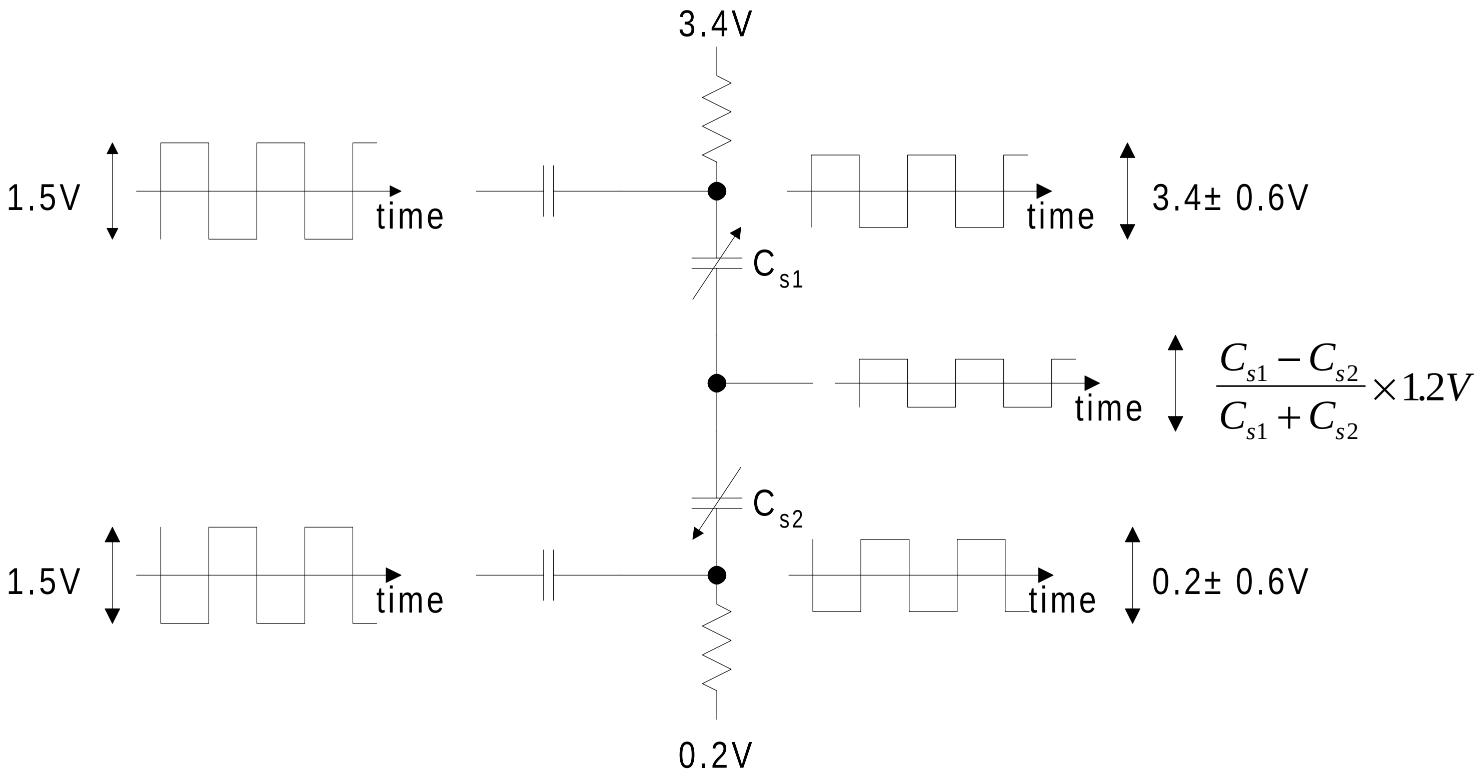
XL-50



increased input range (50g): use all fingers for feedback
(share with sense operation)

Capacitive Interface

XL-50

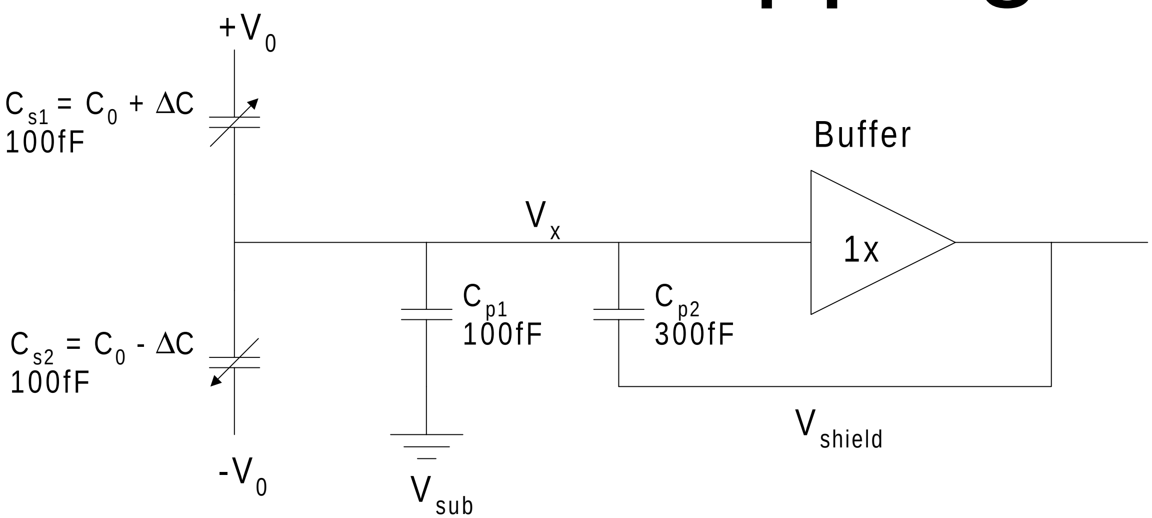


XL-05 vs XL-50 Comparison

	XL-05	**XL-50**	**performance gain**
sense voltage (peak-to-peak)	1.2V	0.6V	2x
resonant frequency (increased mass, softer springs)	12kHz	24kHz	4x
increased sense capacitance			1.5x

Total performance improvement of XL-05 over XL-50: ***12x***

Bootstrapping



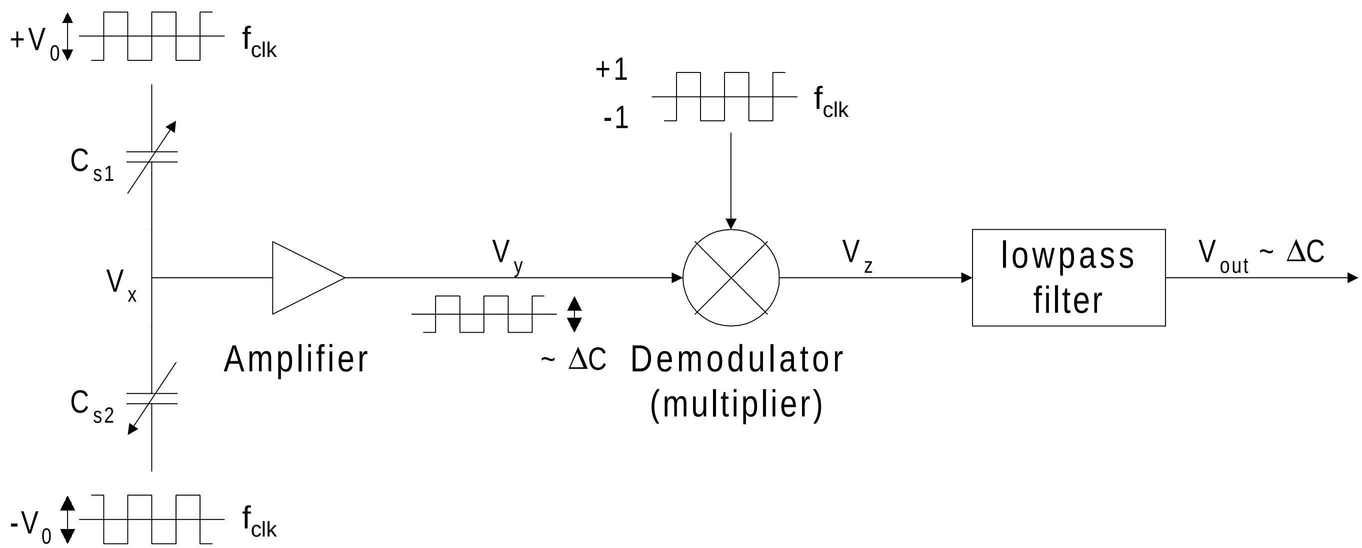
$$V_{out} \approx V_0 \frac{\Delta C}{C_0}$$

- $V_{shield} = V_{out} = V_x$ ---> voltage across C_{p2} is always zero

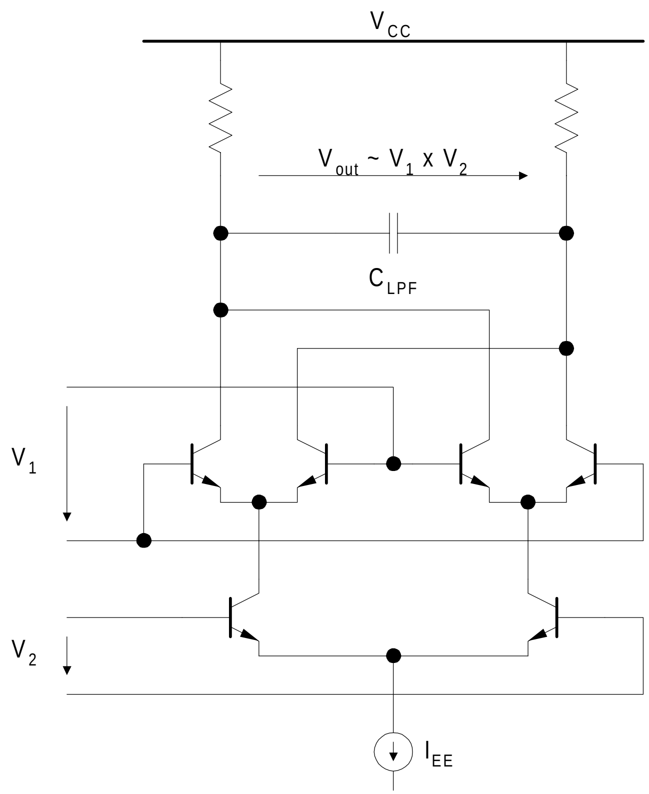
$$V_X = \frac{2\Delta C V_0 + C_{p1} V_{sub}}{2C_0 + C_{p1}}$$

C_{p2} effectively removed

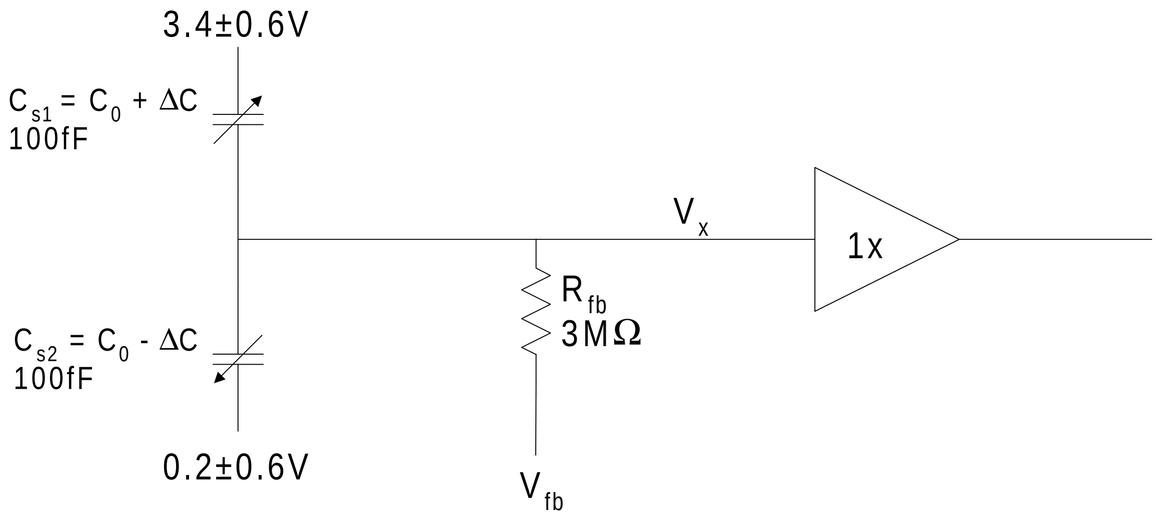
Demodulation



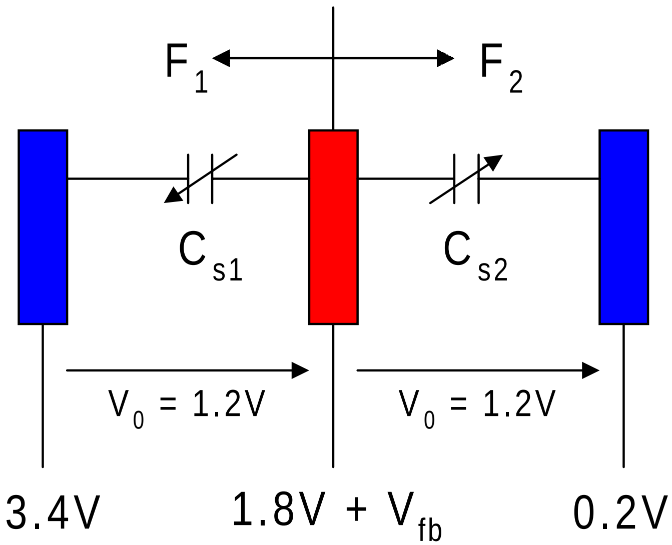
Demodulator & Lowpass Filter



Force-Feedback



Differential Force

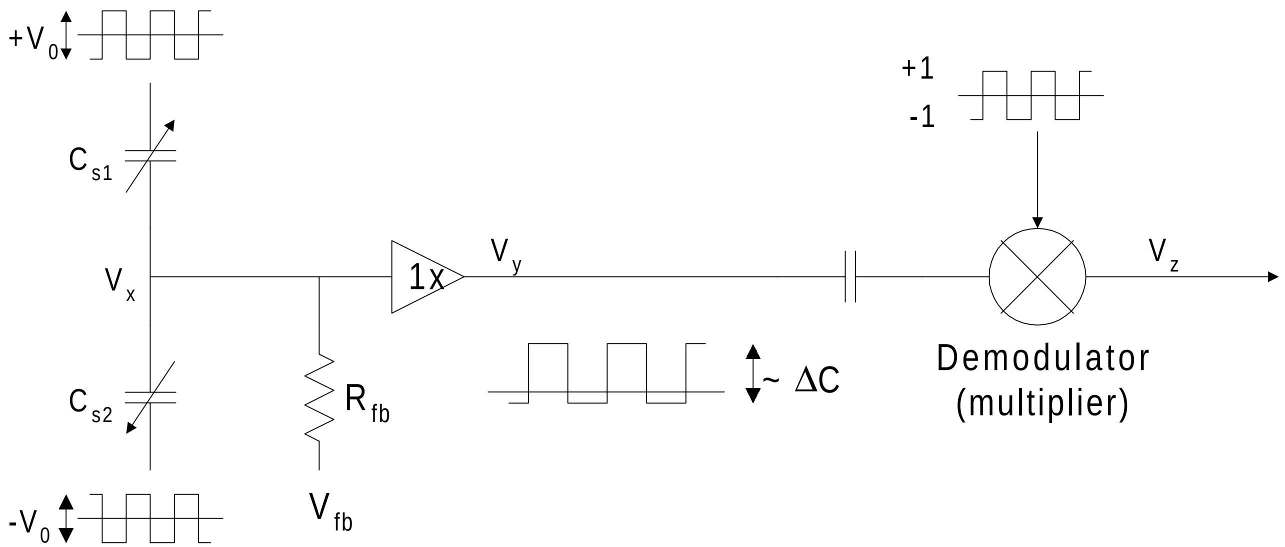


$$\Delta F = F_1 - F_2$$
$$\approx -\frac{1}{2}\frac{C_0}{x_0}\left[\left(V_0 - V_x\right)^2 - \left(V_0 + V_x\right)^2\right]$$
$$\approx \frac{2C_0 V_0 V_x}{x_0} \qquad x << x_0$$

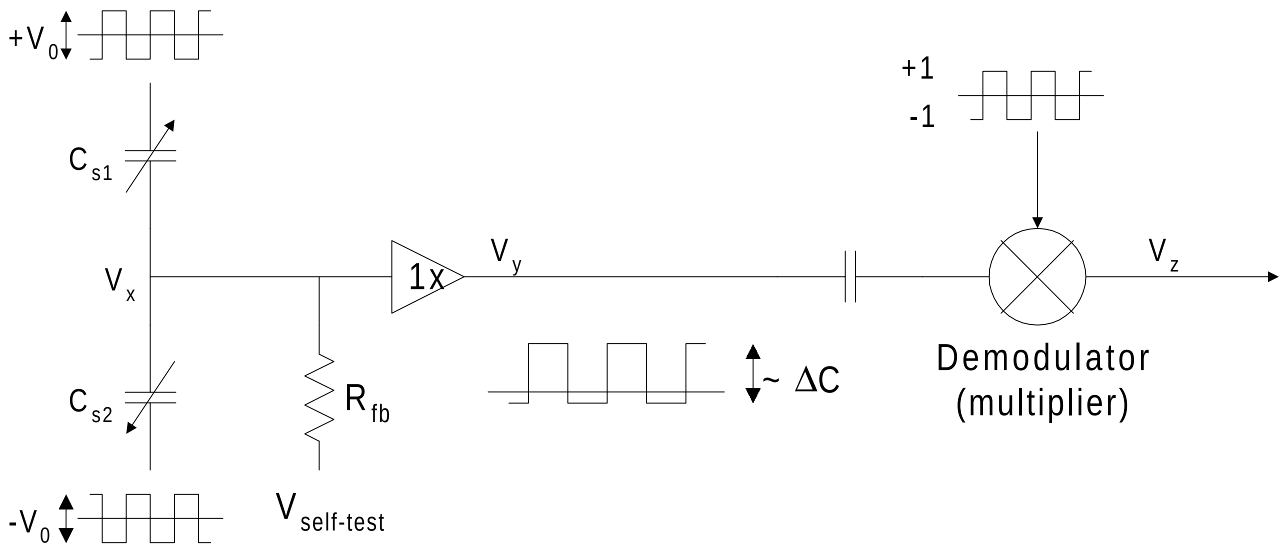
$$\frac{\Delta F}{V_{fb}} \approx 0.1\mu N / V$$

$$\frac{\Delta a}{V_{fb}} = \frac{1}{m} \times \frac{\Delta F}{V_{fb}} = 1000 g / V$$

AC Coupling

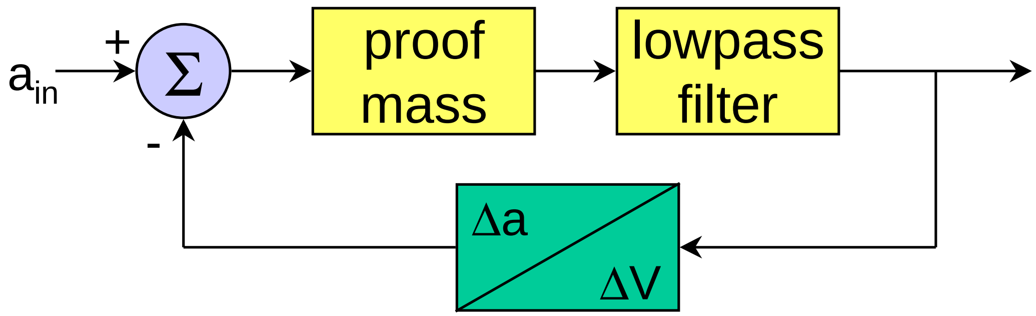


Self-Test



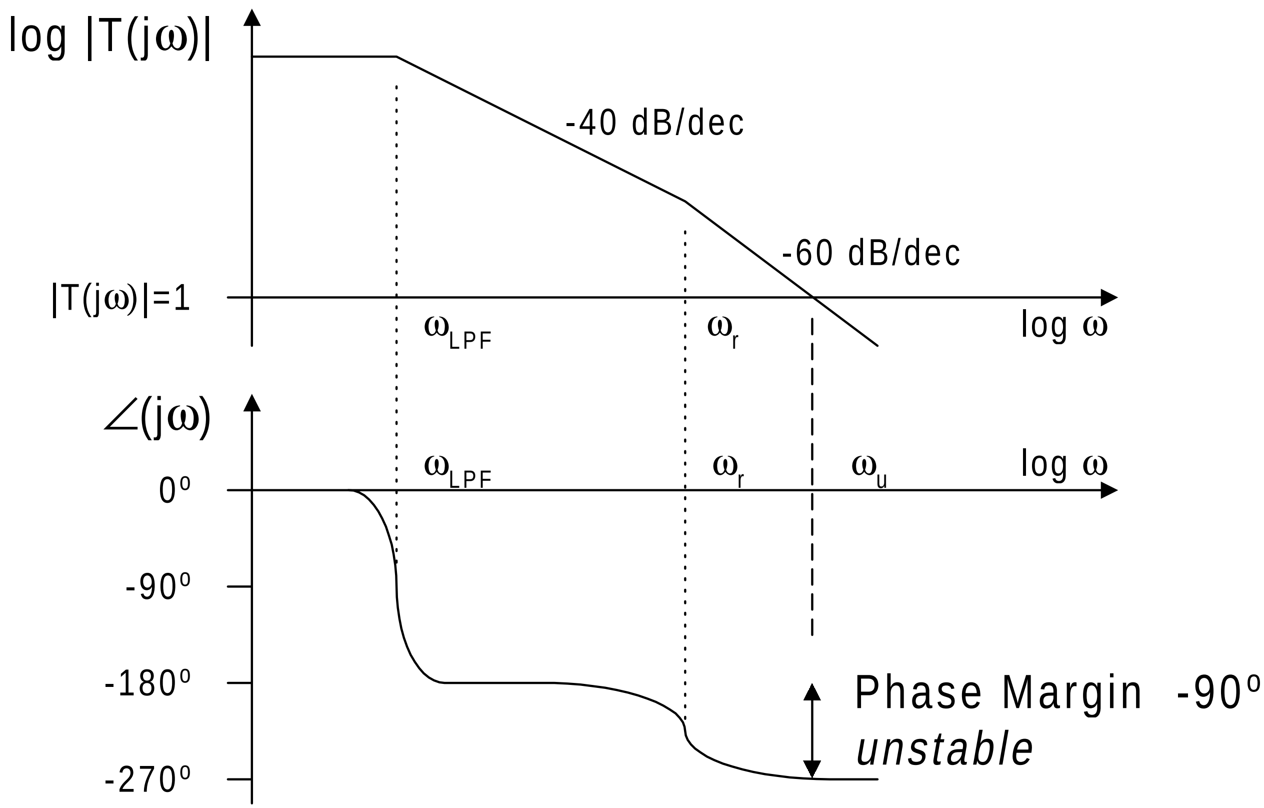
+V0
Cs1
Vx
Cs2
-V0
Rfb
Vself-test
1x
Vy
~ ΔC
+1
-1
Vz
Demodulator
(multiplier)

Stability Analysis

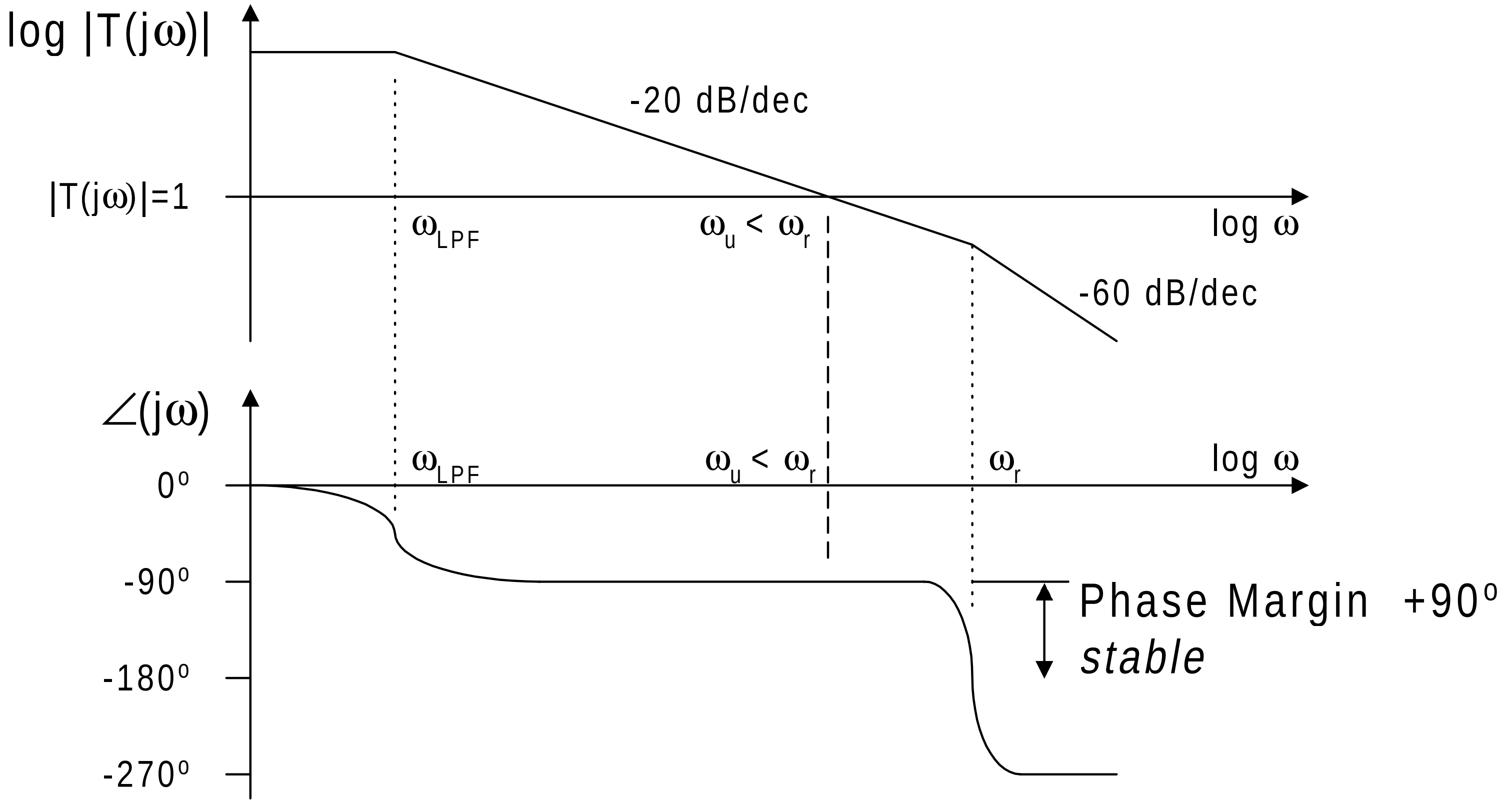


$$\textit{Loop Gain} \qquad T(s) = \underbrace{\frac{1}{s^2 + s\frac{\omega_r}{Q} + \omega_r^2}}_{\textit{proof mass}} \times \underbrace{\frac{1}{1 - \frac{s}{\omega_{LPF}}}}_{\textit{lowpass filter}}$$

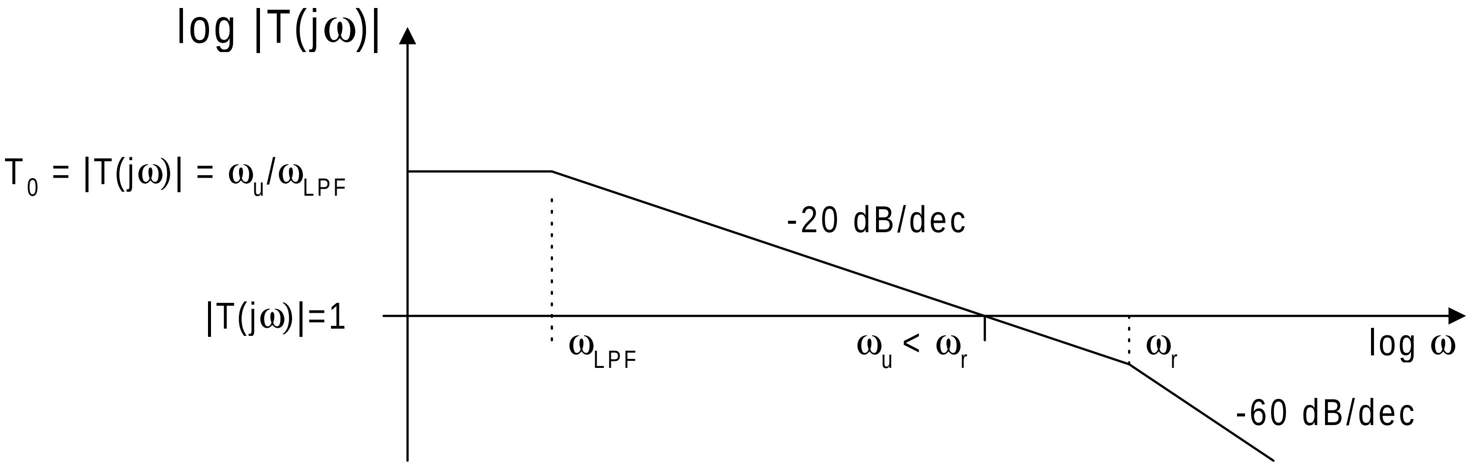
Bode Plot


log |T(jω)|
-40 dB/dec
-60 dB/dec
|T(jω)|=1
ω_LPF
ω_r
log ω
∠(jω)
0°
ω_LPF
ω_r
ω_u
log ω
-90°
-180°
-270°
Phase Margin -90°
unstable

Narrow-Banding



Maximum Loop-Gain

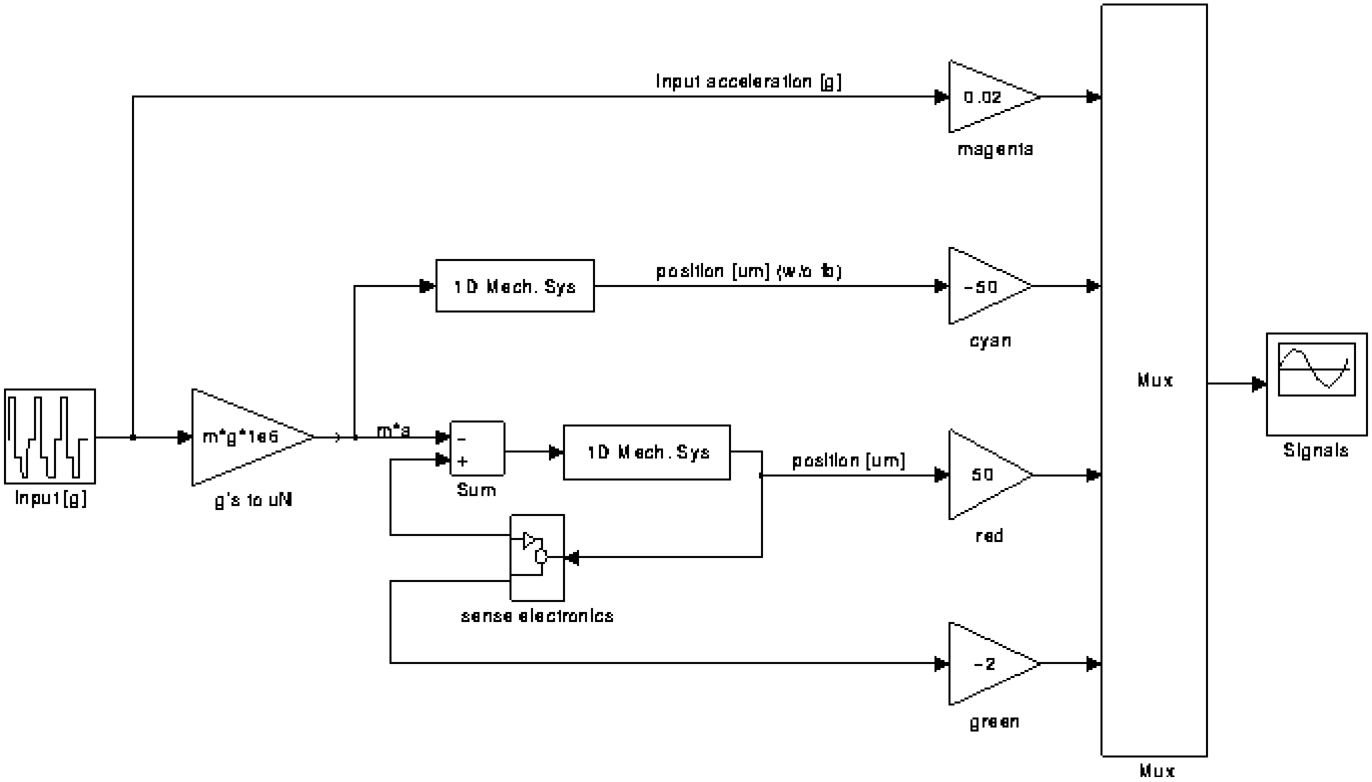


$$T_0 = \frac{\omega_u}{\omega_{LPF}} < \frac{\omega_r}{\omega_{LPF}}$$

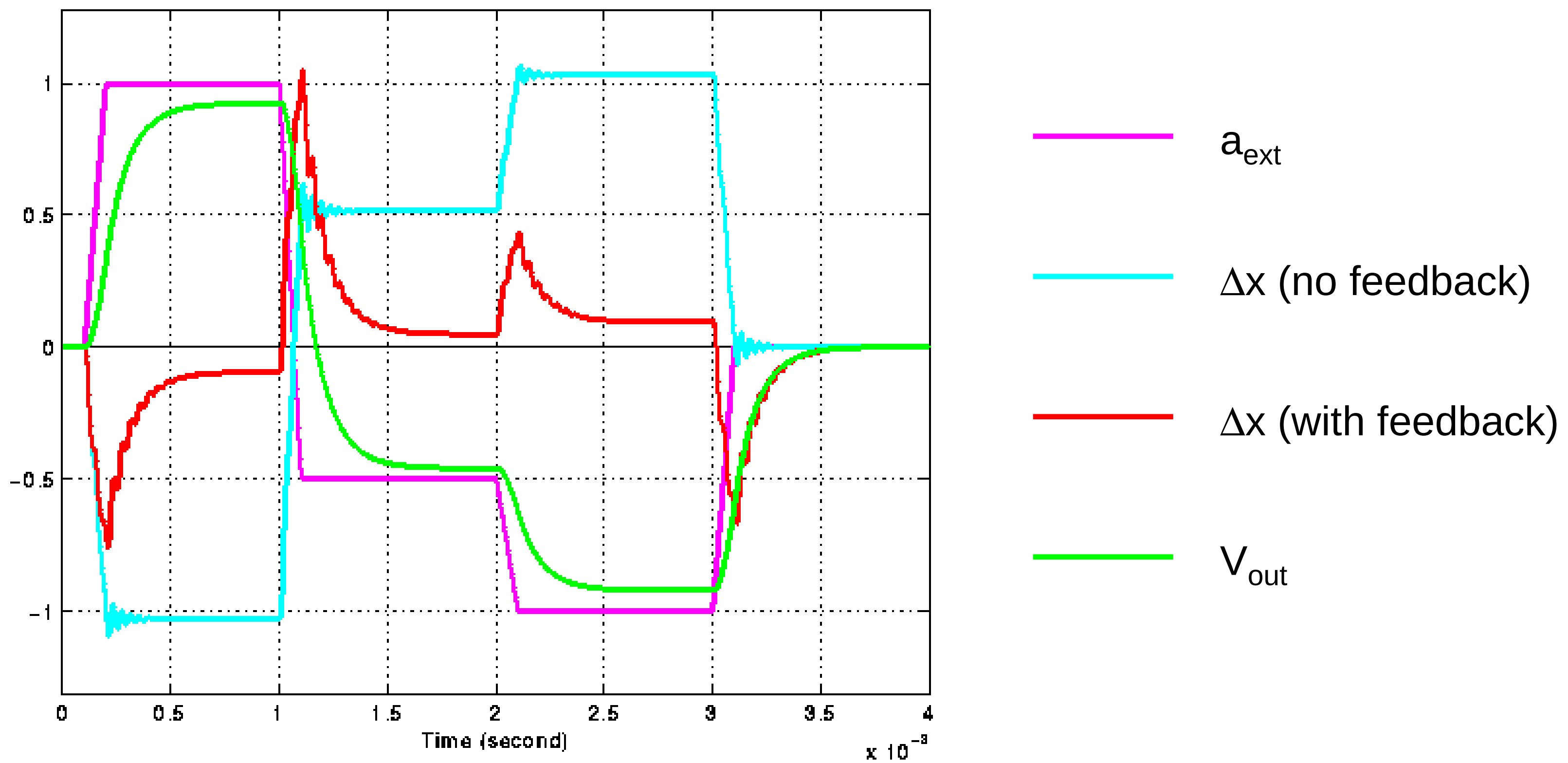
$$= \frac{f_r}{B}$$

$$= \frac{12\ kHz}{1\ kHz} = \underline{12}$$

Matlab Simulation

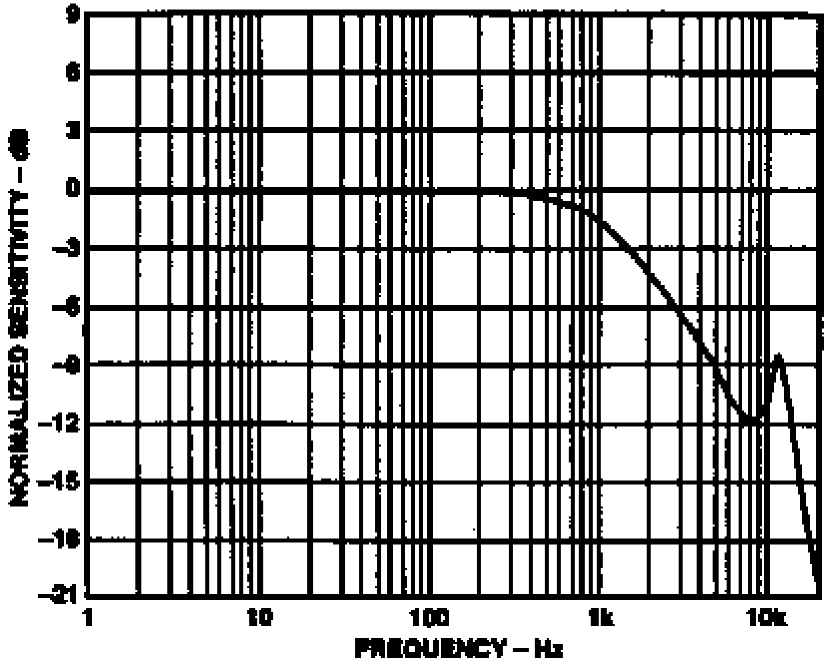


Simulation Result



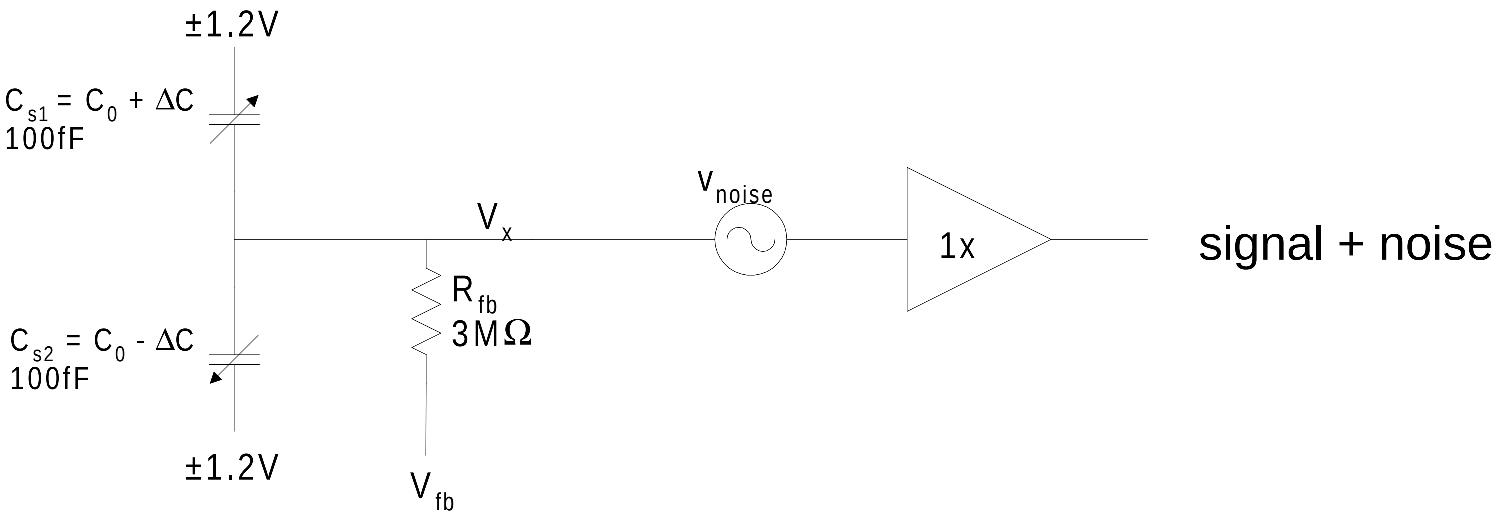
Δx reduced only by factor T_0+1 = 11

Closed Loop Frequency Response



Resonance peak not attenuated by feedback.

Noise Floor


±1.2V
C s1 = C 0 + ΔC
100fF
V x
v noise
1x
signal + noise
R fb
3MΩ
C s2 = C 0 - ΔC
100fF
±1.2V
V fb

Noise Analysis

signal amplitude:

$$V_x = V_0 \times \frac{\Delta C}{C_0}$$

$$= \frac{V_0}{C_0} \times \frac{dC}{dx} \times \Delta x$$

$$= \frac{V_0}{C_0} \times \frac{C_0}{x_0} \times \frac{\Delta a}{\omega_r^2}$$

$$= \frac{V_0}{x_0} \times \frac{\Delta a}{\omega_r^2}$$

signal power:
(assume sinusoidal signal)

$$\overline{v_x^2} = \frac{1}{2}\left(\frac{V_x}{2}\right)^2 = \frac{V_x^2}{8}$$

noise power:

$$\overline{v_n^2} = \left(S_{amp}\right)^2 \Delta f$$

$$\approx \left(500 \, \frac{nV}{\sqrt{Hz}}\right)^2 \Delta f$$

Minimum Detectable Signal

signal power = noise power

$$\sqrt{\frac{\overline{(\Delta a)^2}}{\Delta f}} = \sqrt{8}\,\frac{\omega_r^2\, x_0 S_{amp}}{V_0}$$

$$\approx \sqrt{8}\,\frac{(2\pi \times 12\ krad/s)^2 \times\ 2\mu m\ \times\ 500\,\frac{nV}{\sqrt{Hz}}}{1.2V}$$

$$= \underline{\underline{350\,\frac{\mu g}{\sqrt{Hz}}}}$$

Measured: 600 μg/rt-Hz

Minimum Detectable Displacement

$$\sqrt{\frac{\overline{(\Delta x)^2}}{\Delta f}} = \sqrt{\frac{\overline{(\Delta a)^2}}{\Delta f}} \times \frac{1}{\omega_r^2}$$

$$\approx 0.0006 \frac{nm}{\sqrt{Hz}} \qquad \text{measured:} \quad 0.001 \frac{nm}{\sqrt{Hz}}$$

$$\sqrt{\frac{\overline{(\Delta C)^2}}{\Delta f}} = \sqrt{\frac{\overline{(\Delta x)^2}}{\Delta f}} \times \frac{C_0}{x_0}$$

$$\approx 3 \times 10^{-20} \frac{F}{\sqrt{Hz}} \qquad \text{measured:} \quad 6 \times 10^{-20} \frac{F}{\sqrt{Hz}}$$

Contents of a Can …