

### Position-to-Voltage Conversion

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- To sense position (i.e., displacement), use a capacitive load

Again, have port-to-port I/O symmetry:  $\omega_0$

Brute force approach:

$$\frac{N_o}{V_i}(s) = \frac{1}{R_x + \frac{1}{sC_x} + sL_x + \frac{1}{sC_D}}$$

$$\frac{N_o}{V_i}(s) = \frac{sC_D}{sR_xC_x + 1 + s^2L_xC_x + \frac{1}{sC_D}} = \frac{C_x/C_D}{1 + \frac{sR_xC_x}{1 + C_x/C_D} + s^2 \frac{L_xC_x}{1 + C_x/C_D}}$$

$$\omega_0^2 = \frac{1}{L_xC_x} \rightarrow (\omega_0')^2 = \omega_0^2 (1 + C_x/C_D)$$

$$Q' = \frac{\omega_0' L_x}{R_x} \rightarrow \frac{R_x}{L_x} = \frac{\omega_0'^2}{Q'}, Q' = Q\sqrt{1 + C_x/C_D}$$

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- To sense position (i.e., displacement), use a capacitive load

$$\frac{N_o}{V_i}(s) = \frac{C_x/C_D}{1 + C_x/C_D} \frac{(\omega_0')^2}{s^2 + (\frac{\omega_0'}{Q'})s + (\omega_0')^2}$$

DC Gain Term      Low-Pass Biquad

To maximize gain  $\rightarrow 1$ , need  $C_D \ll C_x$ . (must minimize  $C_D$ )

Note: Can we similar short-cut to the R case.

- Get DC response  $\rightarrow C$ 's dominate.
- Then:

$$\frac{N_o}{V_i}(s) = (\text{DC Gain}) \cdot \frac{1}{s} \cdot \text{LP}(s, \omega_0', Q') \cdot \omega_0'^2$$

Voltage Representing Position

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### Problems With Pure-C Position Sensing

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- To sense position (i.e., displacement), use a capacitive load

Interconnect Band Pad

$$\frac{N_o}{V_i}(s) = \frac{C_x/C_D}{1 + C_x/C_D} \cdot \frac{1}{s} \cdot \text{LP}(s, \omega_0', Q') \cdot \omega_0'^2$$

Integration yields displacement.

To maximize gain, minimize  $C_D$ .

$\Rightarrow$  Problem: parasitic capacitance

$$C_D \rightarrow C_D + C_{pi} + C_{pb}$$

$$\Rightarrow \text{DC Gain: } \frac{C_x/(C_D + C_{pi} + C_{pb})}{1 + C_x/(C_D + C_{pi} + C_{pb})}$$

Output will get smaller!

Remedy: Suppress  $C_p$  via use of op amps.

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### The Op Amp Integrator Advantage

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- The virtual ground provided by the ideal op amp eliminates the parasitic capacitance  $C_p$

$R_2 \gg \frac{1}{sC_2}$  (for biasing)

$P_o = 0.2$

Can drive next stages  $R_i$   $\omega_0$  interference to the formula for!

$$i_o = -i_i(R_2 || \frac{1}{sC_2}) \approx -i_i(\frac{1}{sC_2})$$

$$\approx -\frac{V_i}{R_x} \frac{1}{s} \frac{1}{sC_2} \Rightarrow \frac{N_o}{V_i}(s) = -\frac{1}{R_x C_2} \frac{1}{s}$$

generated ring

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## Differential Position Sensing

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## Differential Position Sensing

• Example: ADXL-50

Proof Mass  
Sense Finger  
Applied Acceleration  
Fixed Electrodes

$$V_o = -V_p + (2V_p) \frac{C_1}{C_1 + C_2}$$

$$= \frac{-V_p C_1 - V_p C_2 + 2V_p C_1}{C_1 + C_2} = V_p \left( \frac{C_1 - C_2}{C_1 + C_2} \right) = V_o$$

Issue: Parasitic Capacitance  

$$V_o = \frac{C_1 C_2}{C_1 + C_2 + C_p} V_p$$
 As before,  $C_p$  reduces gain  
 Solution: use an op amp!

Suspension Beam in Tension

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## Buffer-Bootstrapped Position Sensing

Includes capacitance from interconnects, bond pads, and  $C_{gs}$  of the op amp

Unity Gain Buffer

$C_{gd}$  = gate-to-drain capacitance of the input MOS transistor

- Bootstrap the ground lines around the interconnect and bond pads
  - ↳ No voltage across  $C_p$
  - ↳ It's effectively not there!

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## Effect of Finite Op Amp Gain

Total ADXL-50 Sense C ~ 100fF

Unity Gain Buffer

Get  $z_i = \frac{N_i}{L_i}$ :  $i_i = (N_i - N_o) \leq C_p = N_i \left(1 - \frac{A_o}{1+A_o}\right) \leq C_p = N_i \frac{1}{1+A_o} \leq C_p$

$\therefore \frac{N_i}{L_i} = z_i = \frac{1}{s \left[ \frac{C_p}{1+A_o} \right]}$   $C_{eff} = \frac{C_p}{1+A_o}$

No longer zero!

Ex:  $A_o = 100$ ,  $C_p = 2pF$   
 $\Rightarrow C_{eff} = \frac{2pF}{101} = 20fF$   
 Not negligible compared w/ ADXL-50  $C_{tot} \sim 100fF!$

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Lecture 23m1: Sensing Circuits

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### Integrator-Based Diff. Position Sensing

$+V_P$   
 $-V_P$   
 $i_1$   
 $i_2$   
 $C_1$   
 $C_2$   
 $i_0$   
 $C_p$   
 $0V$   
 $R_2$   
 $C_F$   
 $R_2 \gg \frac{1}{sC_2}$   
 (for biasing)  
 $V_0$   
 $R_o = 0\Omega$   
 Can drive next stage's  $R_1$  w/o interference to transfer function!

$i_0 = i_1 + i_2 = N_p(sC_1) - N_p(sC_2)$   
 $= N_p s(C_1 - C_2)$   
 $\therefore V_0 = -i_0 \left( \frac{1}{sC_F} \right) = -N_p \left( \frac{C_1 - C_2}{C_F} \right)$

$\frac{V_0}{V_P} = - \frac{C_1 - C_2}{C_F} \Rightarrow$  A seemingly perfect differential sensor/amplifier output! ... but only when the op amp is ideal...

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