Overview

- Integrating multiple steps of a single actuator
- Simple beam theory
- Mechanical Digital to Analog Converter

Limits to electrostatics

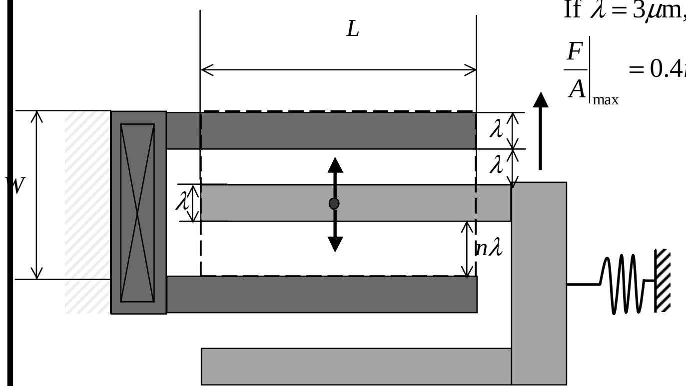
- Residual stress (limits size)
- Pull-in
  - Gap-closing
  - Comb drive
  - Tooth (for comb and gap-closing)
- Thermal noise

Force/Area

$M\text{ax when } n = 1.7$

$\text{If } \lambda = 3\mu\text{m, t} = 50\mu\text{m, V} = 30\text{V}$

$$\left.\frac{F}{A}\right|_{\max} = 0.4 mN / mm^2$$

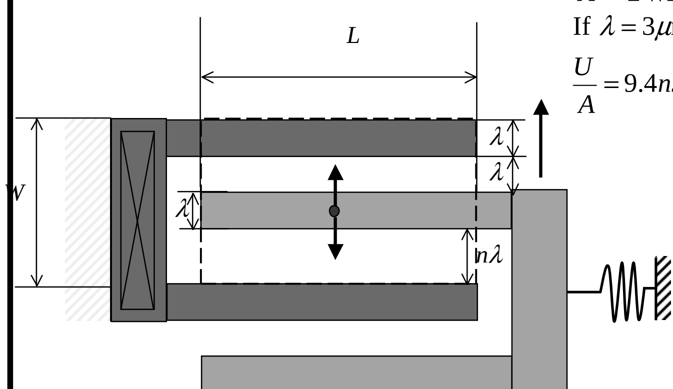


Energy-Area Ratio

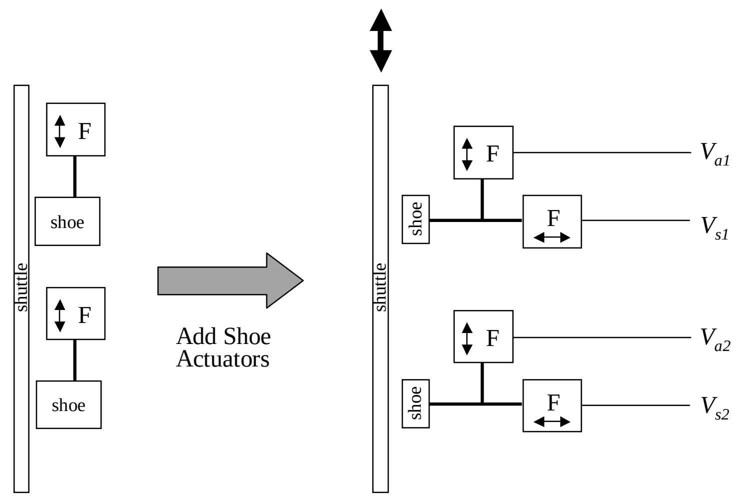
$$\frac{U}{A} = \frac{1}{2}\frac{C}{WL}V^2 = \frac{1}{2}\varepsilon\frac{t}{\lambda W}V^2$$

$\text{If } \lambda = 3\mu\text{m, t} = 50\mu\text{m, V} = 30\text{V}$

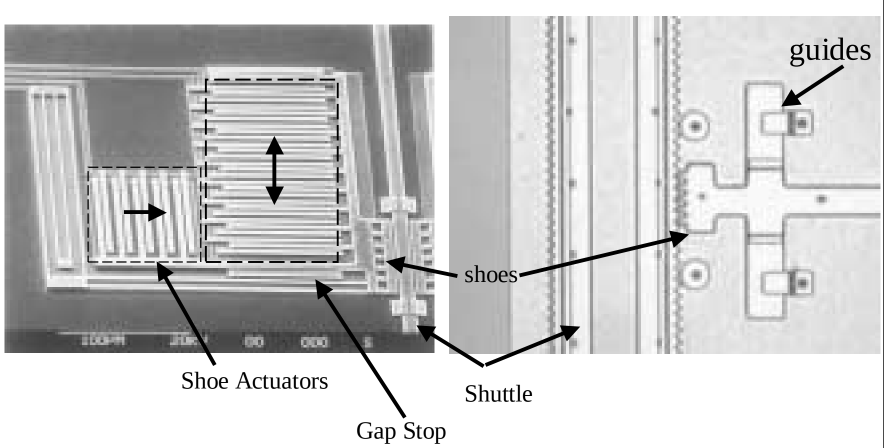
$$\frac{U}{A} = 9.4 nJ / mm^2$$



Inchworm Motor Design

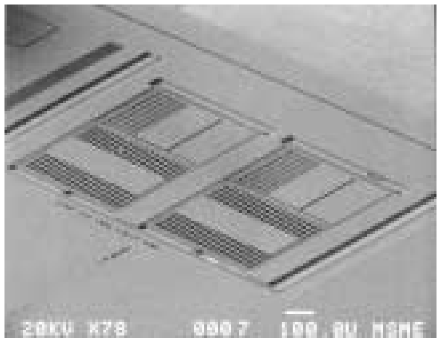


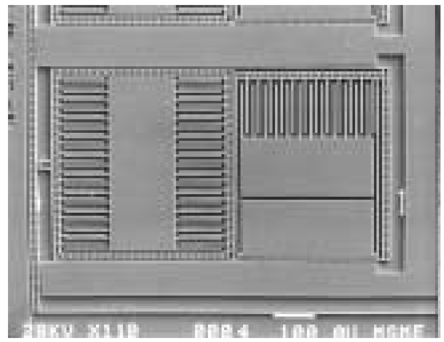
MUMPs Inchworm Motors



Large Force ⇨ Large Structures ⇨ Residual Stress ⇨ Stiction

Silicon Inchworm Motors





1mm

Power Dissipation of the Actuator

$$A_{pads} = 12 \times 4 \times 100^2 \mu m^2 = 4.8 \times 10^5 \mu m^2$$

$$A_{paths} = 12 \times 4 \times 5 \mu m \times 3 \times 10^3 \mu m = 7.2 \times 10^5 \mu m^2$$

$$C_{parasitic} = 24 pF$$

$$F_e = \frac{1}{2} C_g V^2 \Rightarrow C_g = \frac{2F}{V^2}$$

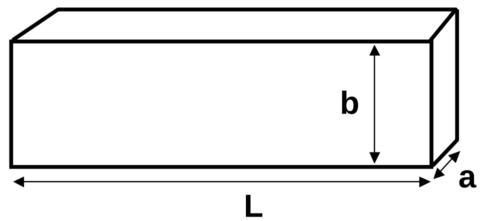
For $F = 1mN \Rightarrow C = 6.7\,pF$

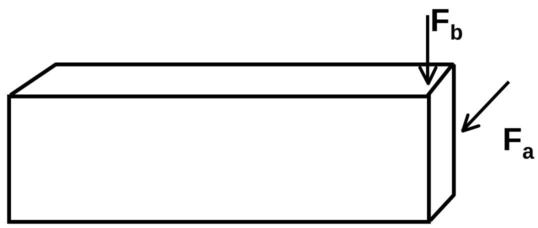
$$P = CV^2 f$$

For $V = 30V,\ f = 1Khz \Rightarrow \underline{P = 27.6 \mu W}$

Springs

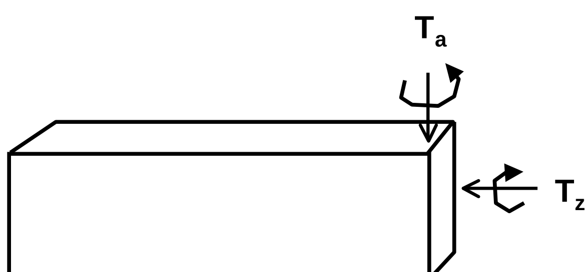
- Linear beam theory leads to
  - $K_a = Ea^3b / (4L^3)$
  - $K_b = Eab^3 / (4L^3)$





Springs

- Linear beam theory leads to
  - $K_{\theta a} = Ea^3b / (12L)$
  - $K_{\theta z} = Ea^3b / (3(1+2\nu) L)$
- Note that T_z results in pure torsion, whereas T_a results in bending as well.



Spring constant worksheet

- Assume that you have a silicon beam that is 100 microns long, and 2um wide by 20um tall. Calculate the various spring constants.
- E_{si} ~ 150 GPa; $G_{si} = E_{si} / (1+ 2\nu) =$ 80 GPa

$a^3b=$	
$K_a=$	
$K_b=$	
$K_{\theta a}=$	
$K_{\theta z}=$	

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Damping

- Two kinds of viscous (fluid) damping
  - Couette: $b = \mu A/g$; $\mu = 1.8\times10^{-5}$ Ns/m^2
  - Squeeze-film: $b \sim \mu W^3L/g^3$
  - μ proportional to pressure
- Dynamics:
  - $m a + b v + k x = F_{ext}$
  - If $x(t) = x_o \sin(\omega t)$ then
    - $v(t) = \omega x_o \cos(\omega t)$
    - $a(t) = - \omega^2 x_o \sin(\omega t)$
  - $-m\omega^2 x_o\sin(\omega t) + b\omega x_o\cos(\omega t) + kx_o\sin(\omega t) = F_{ext}$

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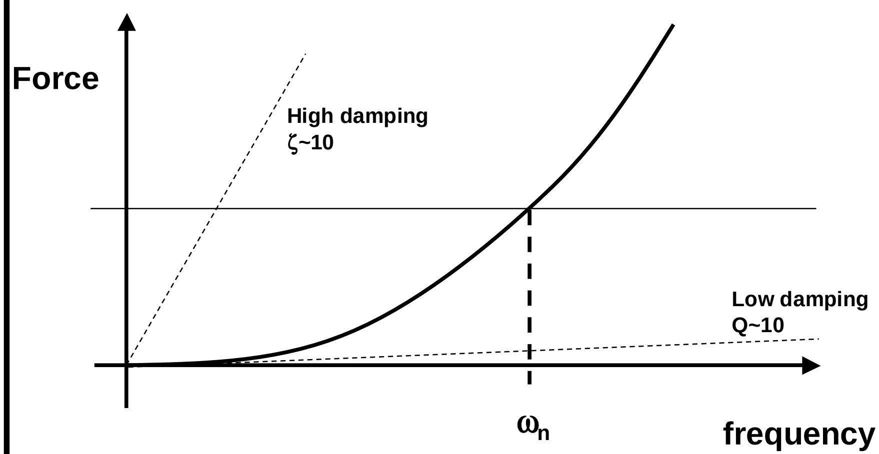
Dynamic forces, fixed amplitude x_o

- $-m\omega^2 x_o \sin(\omega t) + b\omega x_o \cos(\omega t) + k x_o \sin(\omega t) = F_{ext}$



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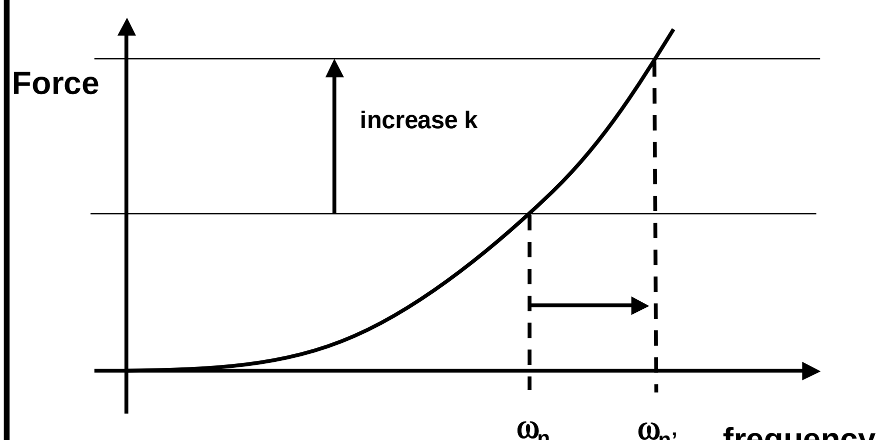
Dynamic forces, fixed amplitude x_o

- $-m\omega^2 x_o \sin(\omega t) + b\omega x_o \cos(\omega t) + k x_o \sin(\omega t) = F_{ext}$



Increasing k raises ω_n but at cost of more force or less deflection

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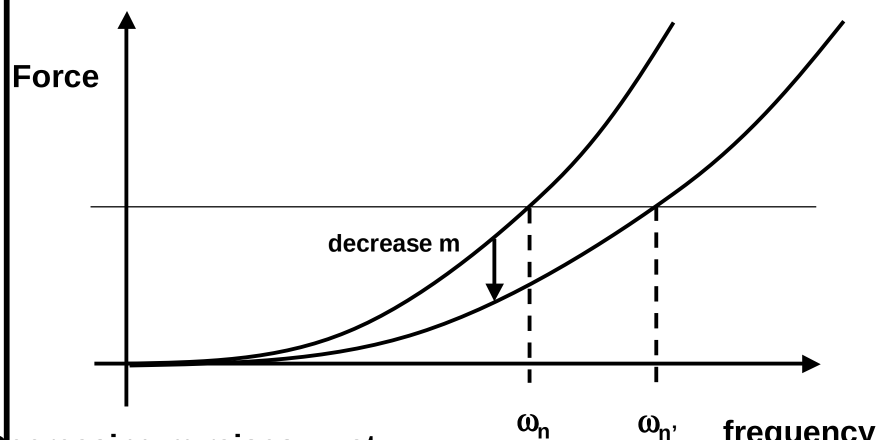
Dynamic forces, fixed amplitude x_o

- $-m\omega^2 x_o \sin(\omega t) + b\omega x_o \cos(\omega t) + k x_o \sin(\omega t) = F_{ext}$



Decreasing m raises ω_n at no cost in force or deflection

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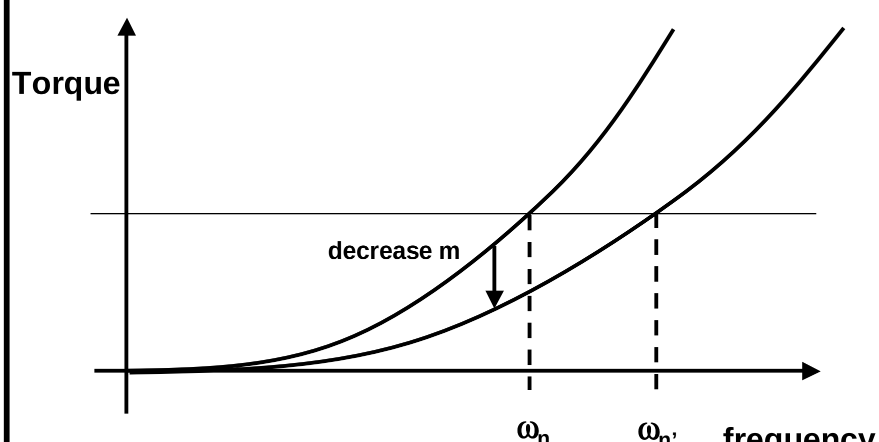
Dynamic forces, fixed amplitude θ_o

- $-J\omega^2 \theta_o \sin(\omega t) + b\omega \theta_o \cos(\omega t) + k_\theta \theta_o \sin(\omega t) = F_{ext}$



Identical result for angular systems with J (angular momentum) instead of m

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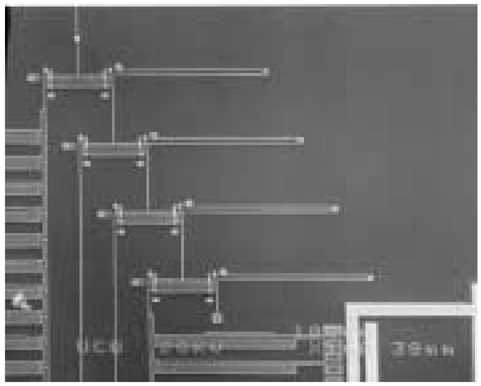
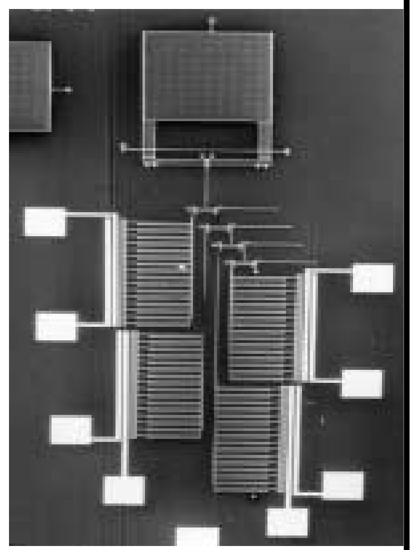
Mechanical Digital to Analog Converter





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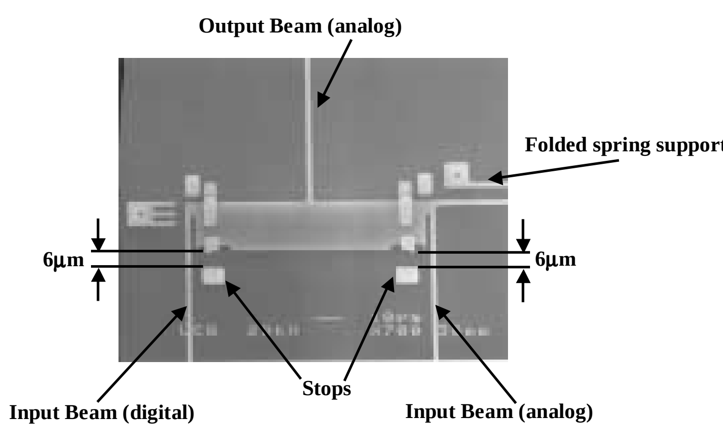
Basic Lever Arm Design



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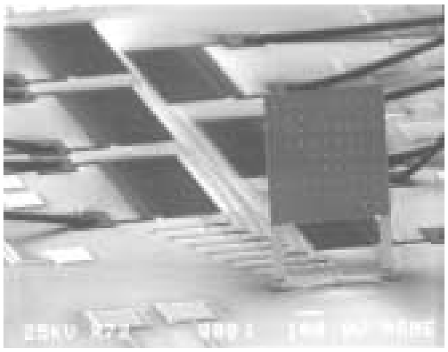
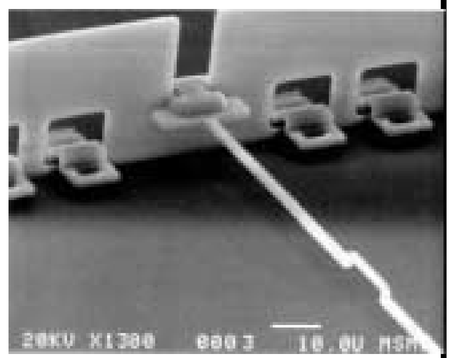
6-bit DAC Implementation





(Courtesy of Matthew Last)

Output of a 6-bit DAC