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EE C247B – ME C218
Introduction to MEMS Design
Spring 2017

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Lecture Module 11: Equivalent Circuits I

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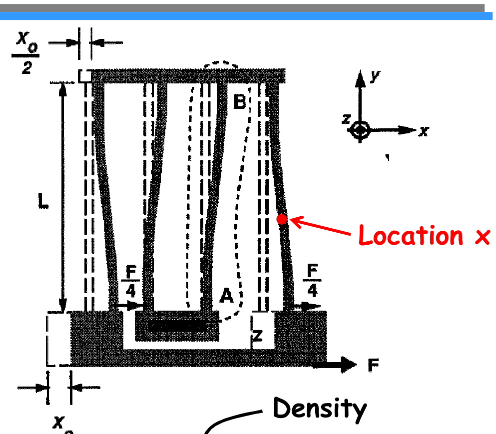
Lecture Outline

- Reading: Senturia, Chpt. 5
- Lecture Topics:
  - Lumped Mass
  - Lumped Stiffness
  - Lumped Damping
  - Lumped Mechanical Equivalent Circuits
  - Electromechanical Analogies

Lumped Parameter Mechanical Equivalent Circuit

Equivalent Dynamic Mass

- Once the mode shape is known, the lumped parameter equivalent circuit can then be specified
- Determine the equivalent mass at a specific location x using knowledge of kinetic energy and velocity



Maximum Kinetic Energy

Density

$$\text{Equivalent Mass} = M_{eq\,x} = \frac{K.E.}{\frac{1}{2}V_x^2} = \frac{\frac{1}{2}\rho A \int_0^{\ell} V^2(x)\,dx}{\frac{1}{2}V_x^2}$$

Maximum Velocity @ location x

Maximum Velocity Function

Equivalent Dynamic Mass

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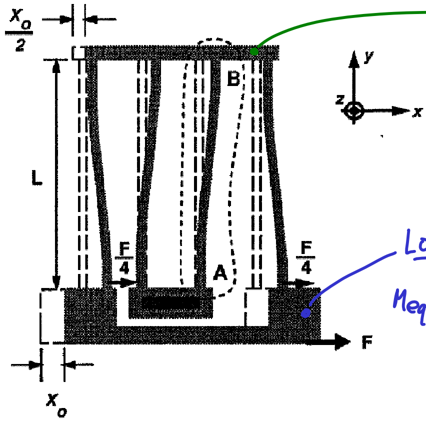
- For the folded-beam structure, we've already determined the maximum kinetic energy
- And in our resonance frequency analysis, we've already determined expressions for velocity



Location on the Truss:

$$M_{eq(truss)} = \frac{KE_{max}}{\frac{1}{2}V_{truss}^2} = \frac{\cancel{\omega_o^2 X_o^2 \left(\frac{1}{2}\right)}\left[M_s + \frac{1}{4}M_t + \frac{12}{35}M_b\right]}{\cancel{\frac{1}{2}}\left(\frac{1}{4}\right)\cancel{\omega_o^2 X_o^2}}$$

$$\therefore M_{eq(truss)} = 4\left[M_s + \frac{1}{4}M_t + \frac{12}{35}M_b\right]$$

Location on the Shuttle:

$$M_{eq(shuttle)} = \frac{KE_{max}}{\frac{1}{2}V_{shuttle}^2} = \frac{\cancel{\omega_o^2 X_o^2 \left(\frac{1}{2}\right)}\left[M_s + \frac{1}{4}M_t + \frac{12}{35}M_b\right]}{\cancel{\frac{1}{2}\omega_o^2 X_o^2}}$$

$$\therefore M_{eq(shuttle)} = M_s + \frac{1}{4}M_t + \frac{12}{35}M_b$$

Equivalent Dynamic Stiffness & Damping

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- Stiffness then follows directly from knowledge of mass and resonance frequency

$$\omega_o = \sqrt{\frac{K_{eq}(x)}{M_{eq}(x)}} \longrightarrow \boxed{K_{eq}(x) = \omega_o^2 M_{eq}(x)}$$

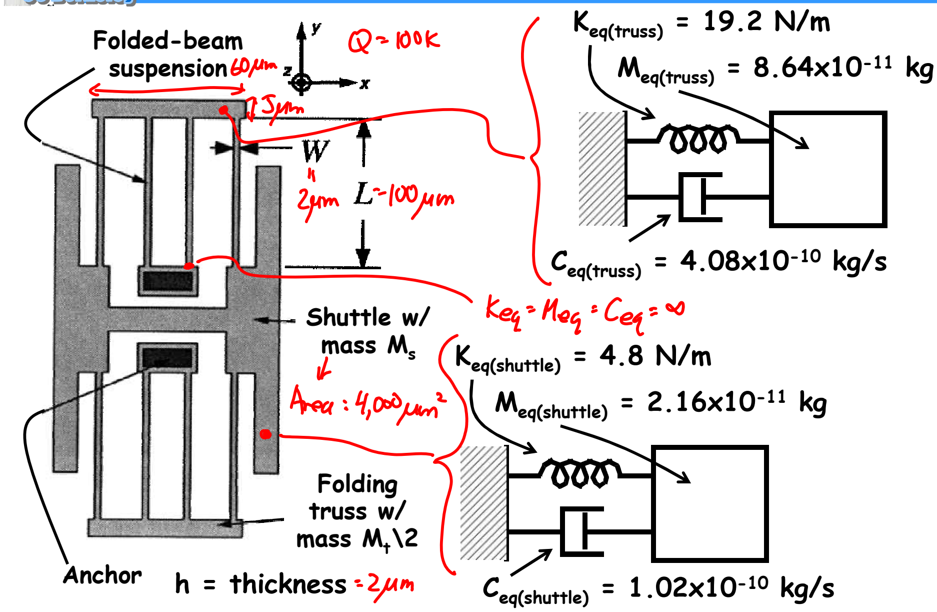
⇒ large equiv. mass & large stiffness go hand-in-hand

- And damping also follows readily from knowledge of Q or other loss measurands

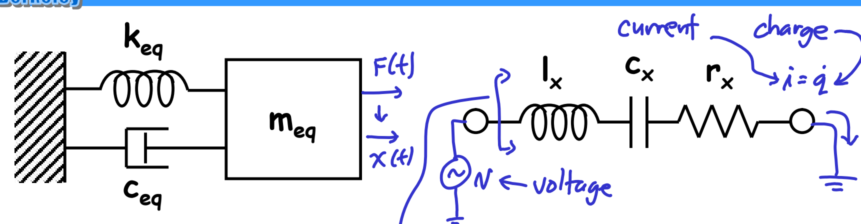
$$Q = \frac{\omega_o M_{eq}(x)}{\underbrace{C_{eq}(x)}_{\text{damping}}} \longrightarrow \boxed{C_{eq}(x) = \frac{\omega_o M_{eq}(x)}{Q} = \frac{\sqrt{K_{eq}(x) M_{eq}(x)}}{Q}}$$

- With mass, stiffness, and damping ⇨ lumped parameter equivalent circuit

Get Potential Energy & Frequency



Electromechanical Analogies



$F(t) = F\cos(\omega t) \rightarrow x(t) = X\cos\omega t$

Equation of Motion:

$$m_{eq}\ddot{x} + c_{eq}\dot{x} + k_{eq}x = F(t)$$

⇒ using phasor concepts:

$$F = j\omega m_{eq}\dot{x} + \frac{k_{eq}}{j\omega}\dot{x} + c_{eq}\dot{x}$$

$v(t) = V\cos\omega t \rightarrow i(t) = I\cos\omega t$

Impedance looking in:

$$\frac{v}{i} = j\omega l_x + \frac{1}{j\omega C_x} + r_x$$

$$v = j\omega l_x i + \frac{(1/C_x)}{j\omega} i + r_x i$$

⇒ by analogy:

$$\boxed{F \rightarrow v \quad \dot{x} \rightarrow i \quad m_{eq} \rightarrow l_x \quad k_{eq} \rightarrow \frac{1}{C_x} \quad C_{eq} \rightarrow r_x}$$

[Parameter Relationships in the Current Analogy]

Electromechanical Analogies (cont)

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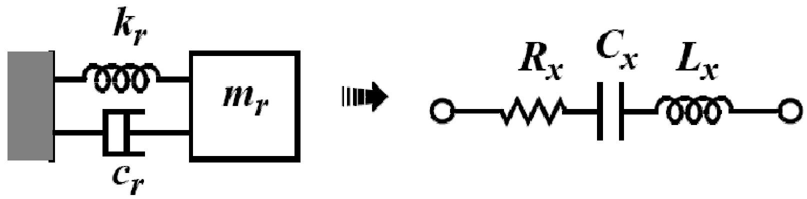

- Mechanical-to-electrical correspondence in the current analogy:

Mechanical Variable	Electrical Variable
Damping, c	Resistance, R
Stiffness^{-1}, k^{-1}	Capacitance, C
Mass, m	Inductance, L
Force, f	Voltage, V
Velocity, v	Current, I

Bandpass Biquad Transfer Function

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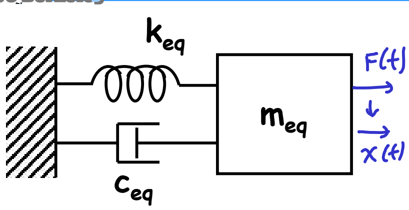
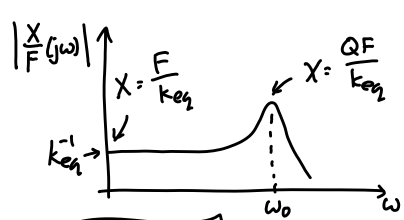




$$\boxed{\frac{X}{F}(j\omega) = \frac{k_{eq}^{-1}}{1-\left(\frac{\omega}{\omega_o}\right)^2 + j\frac{\omega}{Q\omega_o}}}$$

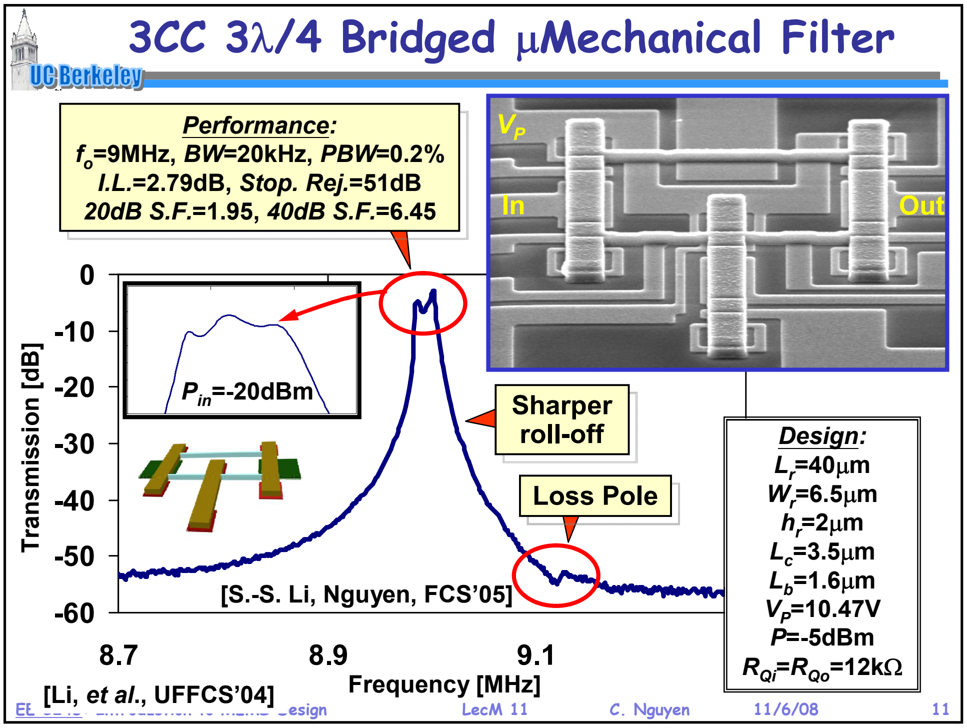
$$F = j\omega m_{eq}\dot{x} + \frac{k_{eq}}{j\omega}\dot{x} + c_{eq}\dot{x}$$

⇒ Converting to full phasor form:

$$F = (j\omega)(j\omega X)m_{eq} + \frac{k_{eq}}{\cancel{j\omega}}(\cancel{j\omega}X) + c_{eq}(j\omega X)$$

$$\frac{X}{F}(j\omega) = \frac{1}{k_{eq}}\left[-\omega^2\frac{m_{eq}}{k_{eq}} + 1 + j\frac{c_{eq}\omega}{k_{eq}}\right]^{-1} = \frac{1}{k_{eq}}\left[-\left(\frac{\omega}{\omega_o}\right)^2 + 1 + j\frac{\omega}{Q\omega_o}\right]^{-1}$$

$$\left[\frac{k_{eq}}{m_{eq}} = \omega_o^2,\ Q = \frac{m_{eq}\omega_o}{c_{eq}} = \frac{k_{eq}}{\omega_o c_{eq}} \rightarrow \frac{k_{eq}}{c_{eq}} = Q\omega_o\right]$$


3CC 3λ/4 Bridged μMechanical Filter
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Performance:
f_o=9MHz, BW=20kHz, PBW=0.2%
I.L.=2.79dB, Stop. Rej.=51dB
20dB S.F.=1.95, 40dB S.F.=6.45
V_P
In
Out
P_{in}=-20dBm
Sharper roll-off
Loss Pole
Design:
L_r=40μm
W_r=6.5μm
h_r=2μm
L_c=3.5μm
L_b=1.6μm
V_P=10.47V
P=-5dBm
R_{Qi}=R_{Qo}=12kΩ
Transmission [dB]
Frequency [MHz]
[S.-S. Li, Nguyen, FCS'05]
[Li, et al., UFFCS'04]
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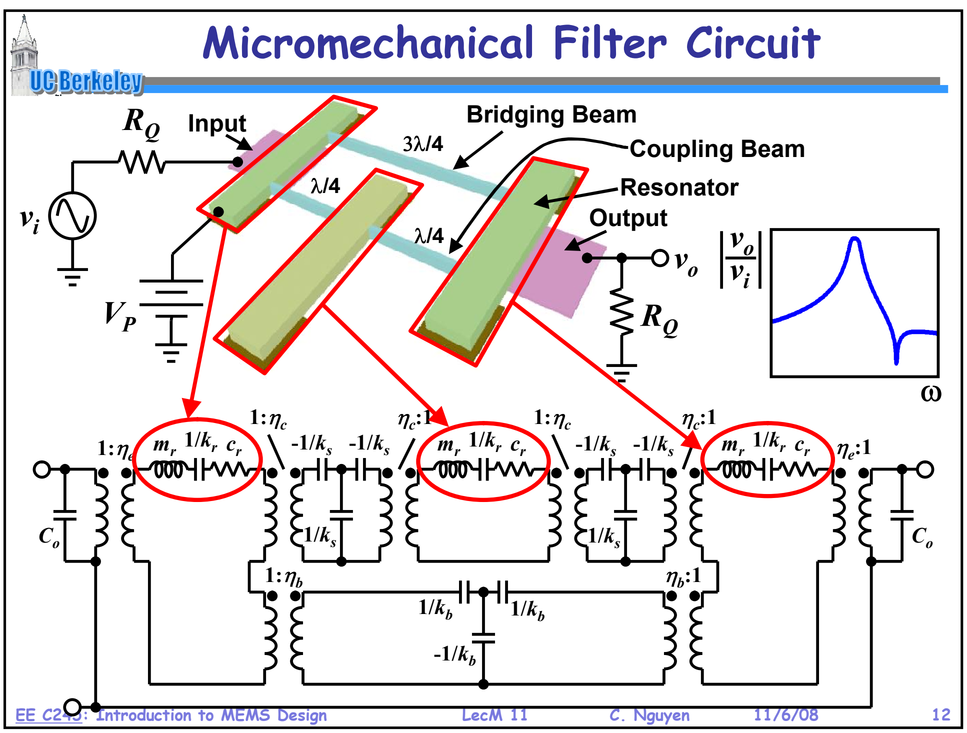
Micromechanical Filter Circuit
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R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
Output
v_i
V_P
v_o
$\left|\frac{v_o}{v_i}\right|$
ω
1:η_e
m_r $1/k_r$ c_r
1:η_c
-1/k_s
η_c:1
1/k_s
C_o
1:η_b
η_b:1
1/k_b
-1/k_b
η_e:1
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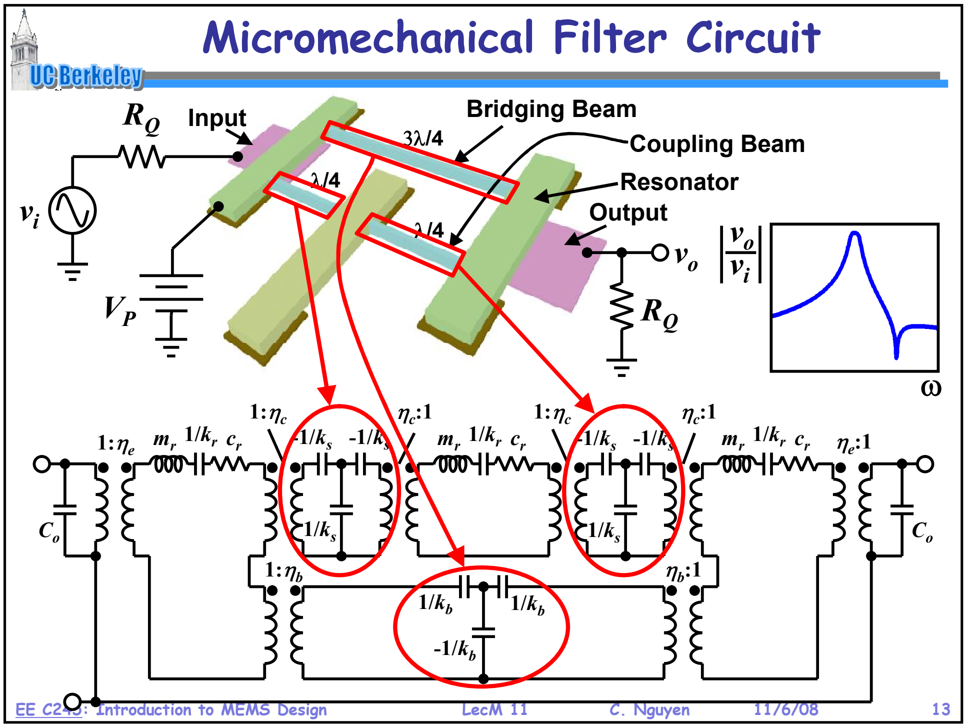
Micromechanical Filter Circuit
UC Berkeley
R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
Output
λ/4
v_i
V_P
v_o
R_Q
$\left|\frac{v_o}{v_i}\right|$
ω
$1:\eta_e$ m_r $1/k_r$ c_r $1:\eta_c$ $-1/k_s$ $-1/k_s$ $\eta_c:1$ m_r $1/k_r$ c_r $1:\eta_c$ $-1/k_s$ $-1/k_s$ $\eta_c:1$ m_r $1/k_r$ c_r $\eta_e:1$
C_o
$1/k_s$
$1/k_s$
C_o
$1:\eta_b$
$\eta_b:1$
$1/k_b$ $1/k_b$
$-1/k_b$
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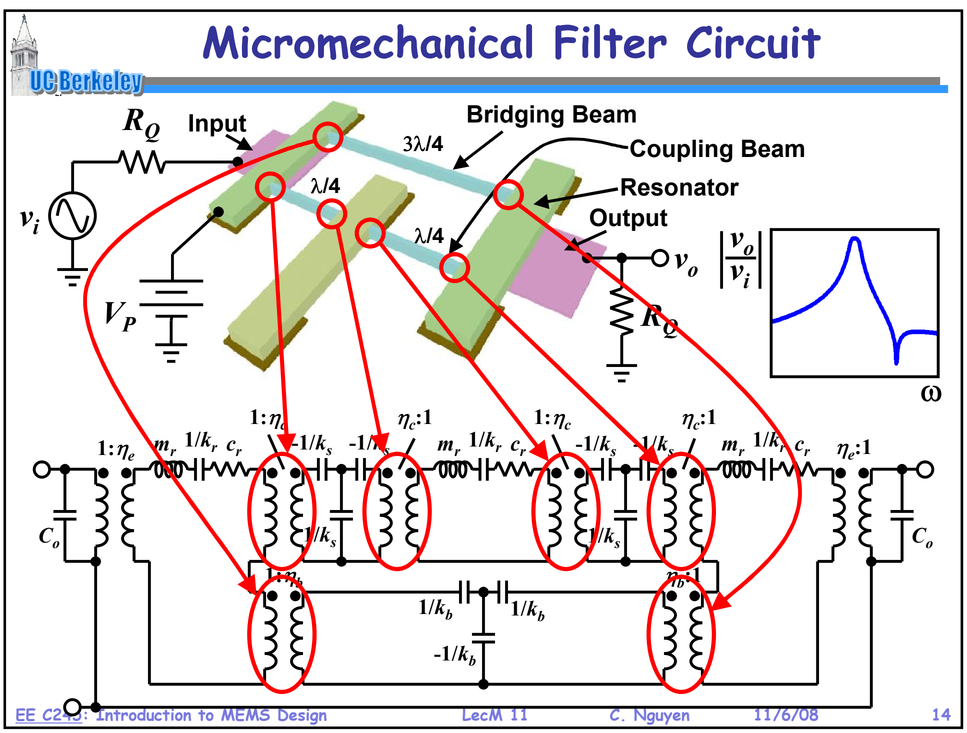
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UC Berkeley
R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
Output
λ/4
v_i
V_P
v_o
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$\left|\frac{v_o}{v_i}\right|$
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$1:\eta_e$ m_r $1/k_r$ c_r $1:\eta_c$ $-1/k_s$ $-1/k_s$ $\eta_c:1$ m_r $1/k_r$ c_r $1:\eta_c$ $-1/k_s$ $-1/k_s$ $\eta_c:1$ m_r $1/k_r$ c_r $\eta_e:1$
C_o
$1/k_s$
$1/k_s$
C_o
$1/k_b$ $1/k_b$
$-1/k_b$
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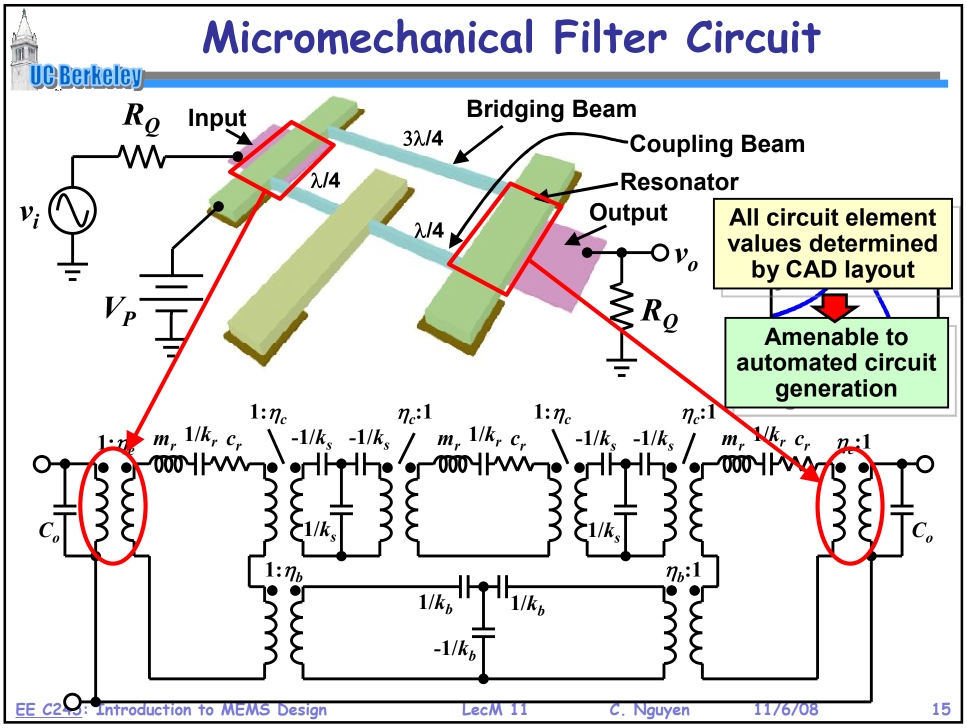
Micromechanical Filter Circuit
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R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
v_i
λ/4
Output
v_o
V_P
R_Q
All circuit element values determined by CAD layout
Amenable to automated circuit generation
$1:\eta_e$
m_r $1/k_r$ c_r
$1:\eta_c$
$-1/k_s$ $-1/k_s$
$\eta_c:1$
$1:\eta_c$
$\eta_c:1$
$\eta_e:1$
C_o
$1/k_s$
$1:\eta_b$
$\eta_b:1$
$1/k_b$ $1/k_b$
$-1/k_b$
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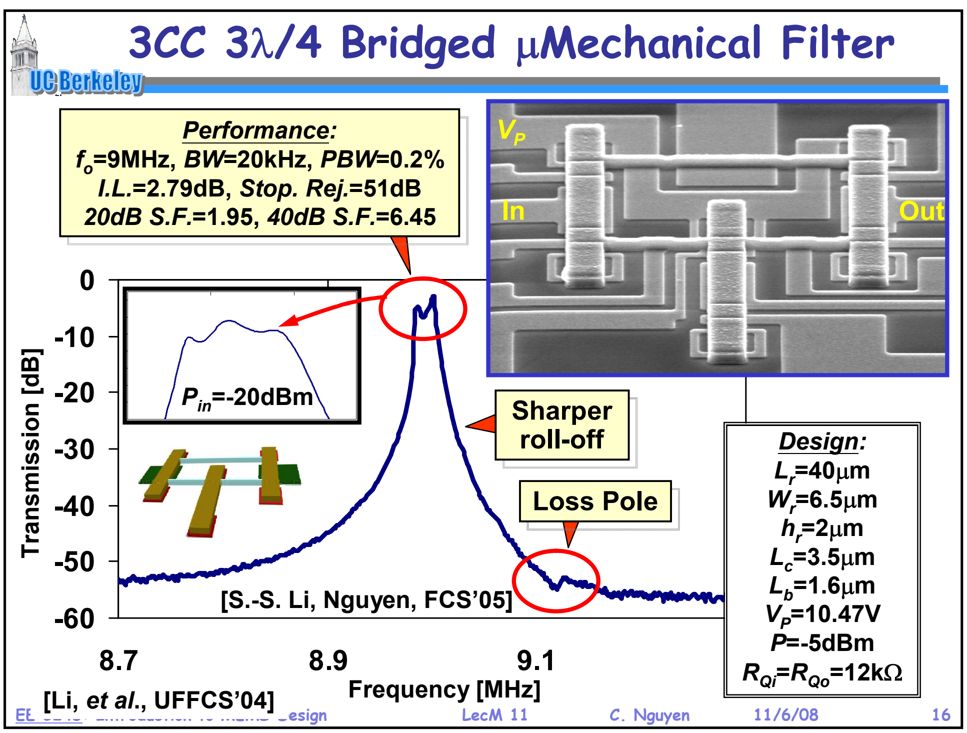
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L_c=3.5μm
L_b=1.6μm
V_P=10.47V
P=-5dBm
R_{Qi}=R_{Qo}=12kΩ
Transmission [dB]
0
-10
-20
-30
-40
-50
-60
8.7
8.9
9.1
Frequency [MHz]
[S.-S. Li, Nguyen, FCS'05]
[Li, et al., UFFCS'04]
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Beam Resonator Equivalent Circuits (Pretty Much the Same Stuff)

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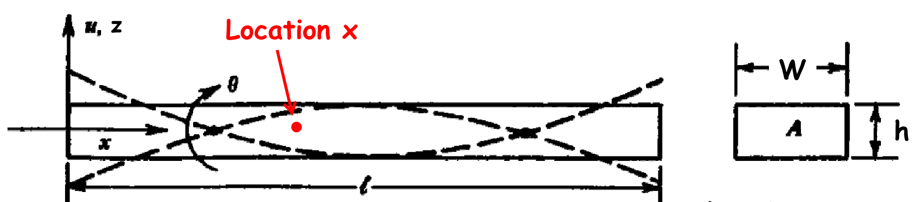
Equivalent Dynamic Mass

- Once the mode shape is known, the lumped parameter equivalent circuit can then be specified
- Determine the equivalent mass at a specific location x using knowledge of kinetic energy and velocity



Maximum Kinetic Energy

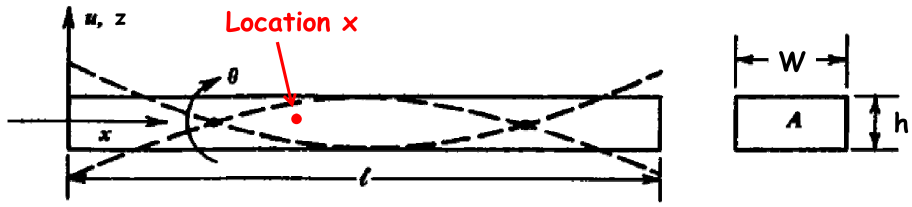
Density

$$\text{Equivalent Mass} = M_{eq\,x} = \frac{K.E.}{\frac{1}{2}V_x^2} = \frac{\frac{1}{2}\rho A \int_0^{\ell} V^2(x)\,dx}{\frac{1}{2}V_x^2}$$

Maximum Velocity @ location x

Maximum Velocity Function

Equivalent Dynamic Mass



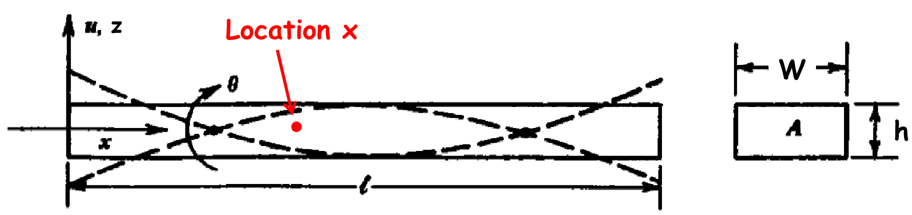
- We know the mode shape, so we can write expressions for displacement and velocity at resonance

Displacement: $u(x) = B\left[\varsigma(\cosh kx + \cos kx) + (\sinh kx + \sin kx)\right]$, $\varsigma = \frac{A}{B}$

$$[v(x) = \omega_0 u(x)] \Rightarrow M_{eq}(x) = \frac{KE_{max}}{\frac{1}{2}[v(x)]^2} = \frac{\cancel{\frac{1}{2}}\rho A \int_0^\ell \cancel{\omega_0^2}[u(x')]^2 dx'}{\cancel{\frac{1}{2}}\cancel{\omega_0^2}[u(x)]^2}$$

$$\boxed{M_{eq}(x) = \frac{\rho A \int_0^\ell \cancel{B^2}[\varsigma(\cosh kx' + \cos kx') + (\sinh kx' + \sin kx')]^2 dx'}{\cancel{B^2}[\varsigma(\cosh kx + \cos kx) + (\sinh kx + \sin kx)]^2}}$$

Equivalent Dynamic Stiffness & Damping



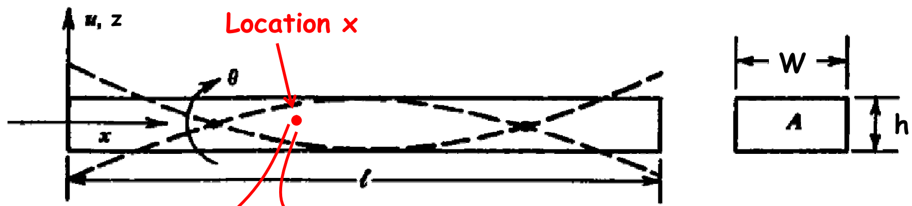
- Stiffness then follows directly from knowledge of mass and resonance frequency

$$\omega_0 = \sqrt{\frac{K_{eq}(x)}{M_{eq}(x)}} \longrightarrow \boxed{K_{eq}(x) = \omega_0^2 M_{eq}(x)}$$

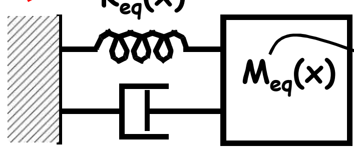
- And damping also follows readily

$$Q = \frac{\omega_0 M_{eq}(x)}{\underbrace{C_{eq}(x)}_{\text{damping}}} \longrightarrow \boxed{C_{eq}(x) = \frac{\omega_0 M_{eq}(x)}{Q} = \frac{\sqrt{K_{eq}(x) M_{eq}(x)}}{Q}}$$

Equivalent Lumped Mechanical Circuit



$$K_{eq}(x) = \omega_o^2 M_{eq}(x)$$

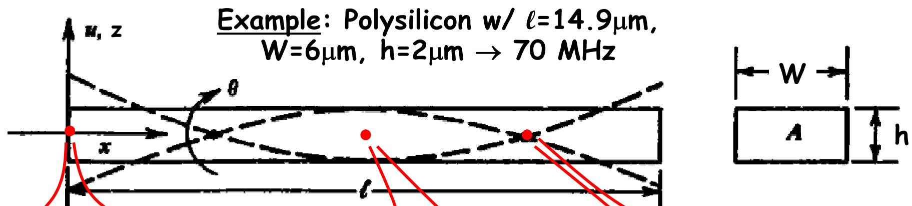


$$M_{eq}(x) = \frac{\rho A \int_o^l [u(x')]^2 dx'}{[u(x)]^2}$$

$$C_{eq}(x) = \frac{\omega_o M_{eq}(x)}{Q}$$

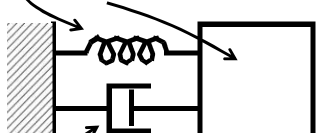
Equivalent Lumped Mechanical Circuit

Example: Polysilicon w/ ℓ=14.9μm, W=6μm, h=2μm → 70 MHz



$K_{eq}(0)$ = 19,927 N/m

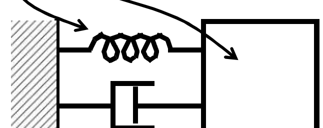
$M_{eq}(0)$ = 1.03x10^{-13} kg



$C_{eq}(0)$ = 5.66x10^{-9} kg/s

$K_{eq}(\ell/2)$ = 53,938 N/m

$M_{eq}(\ell/2)$ = 2.78x10^{-13} kg



$C_{eq}(\ell/2)$ = 1.53x10^{-8} kg/s

K_{eq}(node) = ∞

M_{eq}(node) = ∞

C_{eq}(node) = ∞