EE 245 / NEEM 6441: Introduction to MEMS Design
Homework 3

SUGAR, Thermal Actuation, Resonance, and Electrostatic Instability

1. SUGAR examples (*It is not necessary to turn in the results from this problem, although you're welcome to*). These are taken from the SUGAR User's Guide and are intended to help you learn the basics. Feel free to check out the User's Guide for even more examples at

   a. DC Analysis: This demo shows how to simulate the deflection of a beam due to an external force, where the beam is fixed at one end.

      Netlist creation: The following netlist is created by opening a text editor, entering the 6 lines of netlist shown below, and saved as **cantilever.net**. The three last lines represent an anchor, beam, and force. The first line is a comment, and the 2 "use" lines include a process file for mumps (a std process we will be discussing shortly – process parameters like Young's modulus, etc are included here though), and a standard library. For more information, check out this example in the User's Guide.

      ```
      -- 'cantilever.net'
      use("mumps.net")
      use("stdlib.net")
      anchor {node "substrate"; material=p1, l=10u, w=10u,
      h=10u}
      beam3d {node "substrate", node "tip"; material=p1,
      l=100u, w=2u, h=2u}
      f3d {node "tip"; F=2u, oz=90}
      ```

      Analysis: Once the netlist text file has been created, load it into Matlab using *cho_load*. Then static analysis may be performed to find the equilibrium state of the system using *cho_dc*. Finally, you can display the deformed structure using *cho_display*. For more information, check out this example in the User's Guide.

      ```
      net = cho_load('cantilever.net');
      figure(1); cho_display(net);
      dq = cho_dc(net);
      figure(2); cho_display(net,dq);
      ```

   b. Modal and Steady State Analysis: This demo uses modal analysis to find the resonating frequencies and mode shapes of a 2-D Tang-style resonator (damping not included) as well as a steady-state analysis which outputs the Bode plot of this resonator (damping included – I think, still confirming this fact).

      Netlist creation: The following netlist is created by opening a text editor, entering the netlist shown below, and saved as **multmode.net**.

```
-- 'multmode.net'
use("mumps.net")
use("stdlib.net")
anchor {node "A"; material=p1, l=5u, oz=0, w=10u }
beam2d {node "A", node "D"; material=p1, l=150u, oz=180, w=2u }
anchor {node "B"; material=p1, l=5u, oz=0, w=10u }
beam2d {node "B", node "E"; material=p1, l=150u, oz=180, w=2u }
beam2d {node "D", node "F"; material=p1, l=50u, oz=90, w=5u }
beam2d {node "D", node "E"; material=p1, l=50u, oz=-90, w=5u }
beam2d {node "E", node "G"; material=p1, l=50u, oz=-90, w=5u }
beam2d {node "F", node "H"; material=p1, l=150u, oz=0, w=2u }
beam2d {node "G", node "L"; material=p1, l=150u, oz=0, w=2u }
beam2d {node "H", node "I"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "I", node "O"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "I", node "J"; material=p1, l=75u, oz=-90, w=20u }
beam2d {node "J", node "K"; material=p1, l=75u, oz=-90, w=20u }
beam2d {node "L", node "K"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "K", node "P"; material=p1, l=50u, oz=0, w=20u }
```

Analysis: Once the netlist text file has been created, load it into Matlab using *cho_load*. Then modal analysis may be performed to find the resonant frequencies and mode shapes of the system using *cho_mode*. You can display the various mode shapes using *cho_modeshape*. For a steady-state analysis, *cho_ss* is used instead. For more information, check out this example in the User's Guide.

```
net = cho_load('multmode.net');
figure(1); cho_display(net);
dq = cho_dc(net);
[freq, egv, q0] = cho_mode(net);
figure(2); cho_modeshape(net, freq, egv, q0, 10e-6, 1)
figure(3); cho_modeshape(net, freq, egv, q0, 10e-6, 2)
figure(4); cho_ss(net, dq, 'I', 'y', 'K', 'y');
```

2. Calculate the deflection v. applied voltage for a Comtois-style "heatuator". You'll be making a lot of bad approximations which will tend to balance out reasonably well to give a reasonable approximation of the measured deflection.

$L_{hot} = 240 \ \mu m$
$L_{cold} = 40 \ \mu m$
$W_{hot} = 2 \ \mu m$
$W_{cold} = 2 \ \mu m$
$t_{film} = 2$
$\rho_{si} = 4 \times 10^{-6} \ \Omega\text{-cm}$
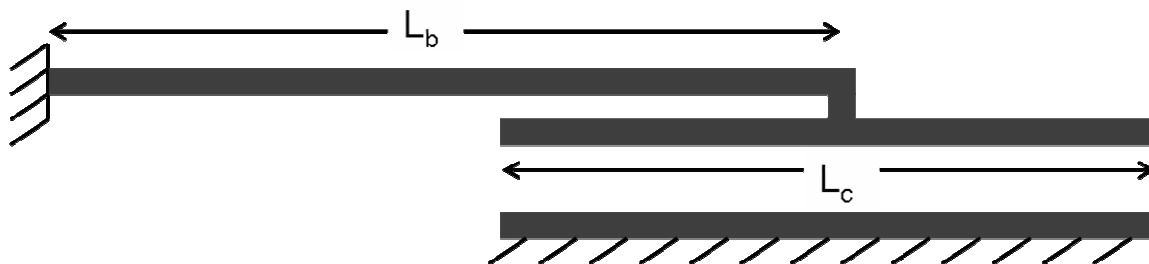$TCE_{si} = 2.3 \times 10^{-6} \ K^{-1}$
$E_{si} = 150 \ GPa$
$K_{si} = 160 \ W/(m*K)$
$K_{air} = 0.03 \ W/(m*K)$

   a. Calculate the resistance of the hot arm (resistance actually varies as a function of temperature and strain)

b. Calculate the power dissipated in the hot arm as a function of the applied voltage.
c. Estimate the thermal conductance along the length of the hot arm.
d. Estimate the thermal conductance of the substrate.
e. Assuming that all of the power dissipated in the hot arm enters at the tip (bad assumption) and flows through the two conductances above in parallel to thermal ground (bad assumption), calculate the temperature rise at the tip of the beam.
f. Assuming that the whole beam heats up uniformly to the temperature calculated above (bad assumption), calculate the strain and resulting axial force in the beam due to the thermal expansion if the hot beam is not allowed to expand.
g. Calculate the moment applied to the end of the short/cool beam.
h. Calculate $K_{\theta\theta}$ for the short beam, and the resulting angular deflection, ignoring the other spring constants in the problem.
i. Write down the lateral tip deflection as a function of applied voltage.

3. Design a Tang-style (dog-bone) resonator with a resonant frequency of $\omega_n = 20$ kHz. Give your resonator double-folded flexures and assume a material thickness of 2 μm.

   a. List the flexure lengths and widths, spring constant, and mass.
   b. Assuming an air gap of 2 μm to the substrate beneath your resonator, what is the quality factor? If I want to keep the same natural frequency, is it possible to make any geometric changes from your original design to increase Q?
   c. Design this resonator in SUGAR and confirm your designed natural frequency.
   d. Resonators have become an interesting topic for those interested in RF MEMS. Assume a comb drive array exists on one side of the resonator for driving it, and a comb drive on the opposite side exists for sensing (a topic to be covered a little later). What do I sense (qualitatively) if I apply a broad band signal (signal with many frequency components) on one side of the resonator? Does this remind you of any electrical equivalents?
   e. Given the same actuator mass in your design above, what spring constant would be required to change the resonant frequency to 900 MHz (a common radio band)? Is this style of resonator practical for this frequency?

4. You have designed a gap closing actuator of length L_c on the end of a cantilever of length L_b etched into 40 μm thick SOI film. Assume the actuator beam is rigid and the beam width and initial electrostatic gap are 2 μm. Calculate the pull-in voltage when:

a. Lb = 1000 μm, Lc = 100 μm
b. Lb = 100 μm, Lc = 1000 μm
c. Lb = 100 μm, Lc = 100 μm
d. Compare your results to SUGAR