Simulating RF MEMS

David Bindel

UC Berkeley, CS Division
# Collaborators

<table>
<thead>
<tr>
<th>Faculty</th>
<th>Grad students</th>
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<tbody>
<tr>
<td>A. Agogino (ME)</td>
<td>D. Bindel (CS)</td>
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<tr>
<td>Z. Bai (Math/CS)</td>
<td>J.V. Clark (AS&amp;T)</td>
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<tr>
<td>J. Demmel (Math/CS)</td>
<td>D. Garmire (CS)</td>
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<td>S. Govindjee (CEE)</td>
<td>T. Koyama (CEE)</td>
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<td>R. Howe (EE)</td>
<td>R. Kamalian (ME)</td>
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<td>J. Nie (Math)</td>
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<td>S. Bhave (EE)</td>
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Goal: “Be SPICE to the MEMS world”
- Fast enough for early design stages
- Simple enough to attract users
- Support design, analysis, optimization, synthesis
- Verify models by comparison to measurement
Why RF resonators?

Microguitars from Cornell University (1997 and 2003)

- Frequency references
- Sensing elements
- Filter elements
- Neural networks
- Really high-pitch guitars
Micromechanical filters

Mechanical high-frequency (high MHz-GHz) filter
Saves power and cost over electronic filters
Advantage over piezo-actuated quartz SAW filters
Integrated into chip
Low power
Governing equations: forced response

Time domain:

\[ Mu'' + Cu' + Ku = P\phi \]
\[ y = V^T u \]

Frequency domain:

\[ H(\omega) = V^T (-\omega^2 M + i\omega C + K)^{-1} P \]
\[ \hat{y} = H\hat{\phi} \]
First proposed design: Checkerboard

- Array of loosely coupled resonators
- Anchored at outside corners
- Excited at northwest corner
- Sensed at southeast corner
- Surfaces move only a few nanometers
Design questions

- Where should drive and sense be placed?
- How should the individual resonators be connected?
- How should the system be anchored?
- How many components? What topology?
- What size should the components be?
Checkerboard response

95 MHz

100 MHz
Checkerboard response

Corner-connected response

Beam-connected response

Corner-connected details  Beam-connected details
Checkerboard response: 4-by-4

Frequency response for corner-coupled resonator

Amplitude (dB)

Frequency (Hz)

Phase

Frequency (Hz)
Shear ring resonator

- Ring is driven in a shearing motion
- Can couple ring to other resonators
Current questions

- How do we model damping?
- How do we compute frequency response quickly?
- How do we track dependence on geometry?
- How do we optimize designs?
Energy loss and $Q$

- Goal: strong output signal and high $Q$
- Challenge: Model details of energy loss
  - Anchor loss
  - Thermoelastic damping
  - Akheiser damping
  - Air damping
- How are losses affected by fabrication errors (e.g. anchor misalignment)?
Anchor loss

$f_{\text{damp}} \approx 11.5\text{MHz}$ and $Q \approx 50 \quad f_{\text{damp}} \approx 15\text{MHz}$ and $Q \approx 160$

- Impose artificial boundary conditions (ABCs)
- Mimic a semi-infinite domain (non-reflecting BC)
- Two main classes: easy + inaccurate, hard + accurate
Thermoelastic losses

- Heating coupled to volumetric strain rate
- Diffusion of heat $\implies$ irreversible loss
- Zener approximated the effect for beams
- Finite element discretization works more generally
- Accelerate solution with a perturbation method
Differentiate eigenvalue equation

\[ K(s)q(s) = \lambda(s)M(s)q(s) \]

Predictor-corrector iteration

Convergence criteria, step control based on

\[ |q(s_k)^Tq(s_{k+1})| \]
Reduction of governing equations

- Typically reduce the problem size while computing.
- Seek the best approximate solution from a family of shapes
- Basis of
  - Finite element methods (infinite-dim $\rightarrow$ finite)
  - Iterative methods for eigenvalue problems
  - Iterative solvers for linear systems
  - Lumped circuit models (modal mass and stiffness)
- Trick is to choose a good family of approximants
Model reduction

Approximate with a set of global shape functions
- Chosen from a Krylov subspace
- Chosen from analysis of substructures
- Preserve second order system structure

Sun Ultra 10
Sec \( n \)
ROM: 28 4834
Full: 1474 50
Transfer function optimization

Choose geometry to make a good bandpass filter

What is a “good bandpass filter?”
- \(|H(\omega)|\) is big on \([\omega_l, \omega_r]\)
- \(|H(\omega)|\) is tiny outside this interval

How do we optimize?
- Overton’s gradient sampling method
- Use Byers-Boyd-Balikrishnan algorithm for distance to instability to minimize \(|H(\omega)|\) on \([\omega_l, \omega_r]\)
- Small Hamiltonian eigenproblem (with ROM)
Software framework

Simulations done with FEAPMEX
- Matlab interface to the FEAP finite element code
- Provides both FEAP and Matlab capabilities
- Interface code is publically available
Conclusions

RF MEMS are an interesting source of computational problems
  - Understanding the physics
  - Applying numerical tools

http://bsac.berkeley.edu/cadtools/sugar/sugar/
http://www.cs.berkeley.edu/~dbindel/feapmex.html