



Visualización y Prueba Dinámica de MEMS

(MEMS Dynamic Testing and Visualization)

Keynote Speech

Semana Nacional de Ingenieria Electronica (SENIE) 2009
Ocotlan, Jalisco, Mexico

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Introducción



La montaña de Sandía



Así se llama.



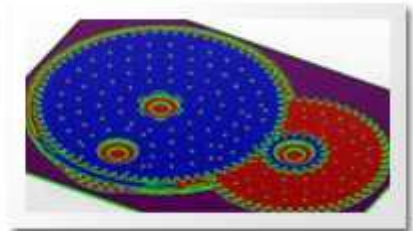
- Overview of Sandia's activities in MEMS
- Case study 1: Mechanical shocks in Radio-Frequency MEMS
- Case study 2: Measurement of gas damping
- Sensors testing examples
- Actuator examples
- Conclusion

Sandia conducts many research activities in MEMS



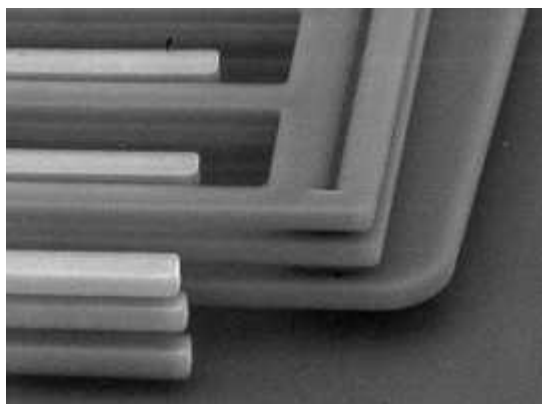
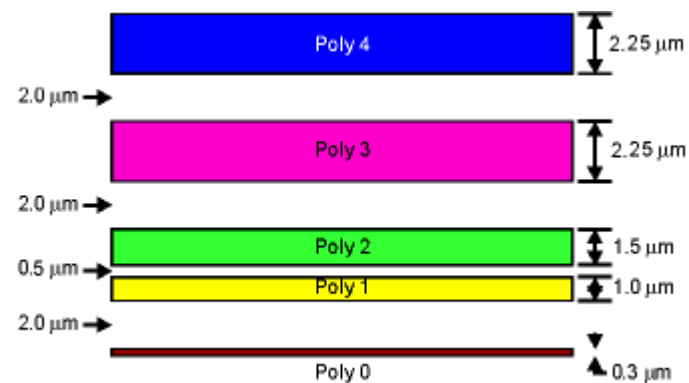
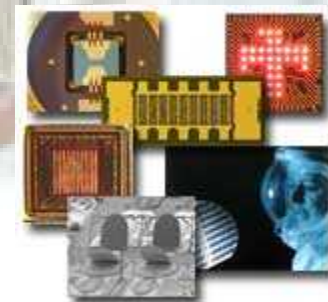
- MEMS realization requires the integration of
 - Design with analysis
 - Fabrication
 - Packaging
 - Testing

First step: Design with analysis





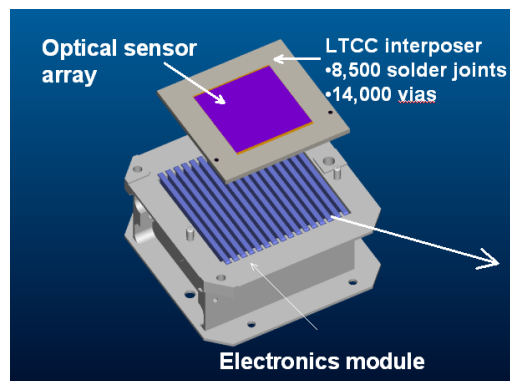
Second step: Fabrication





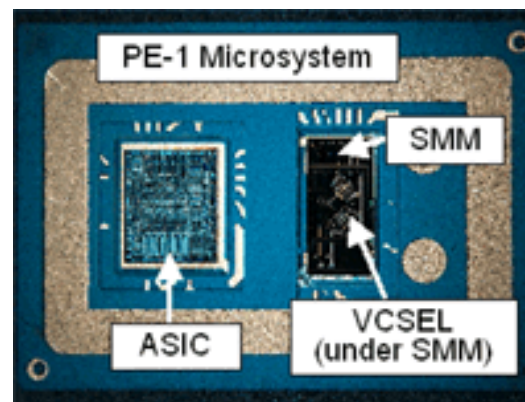
Third step: Packaging

- Difference from electronics packaging: MEMS moves.
- High capability, small volume packaging solutions are necessary to microsystems.
- Advanced packaging integrates MEMS into microsystems.



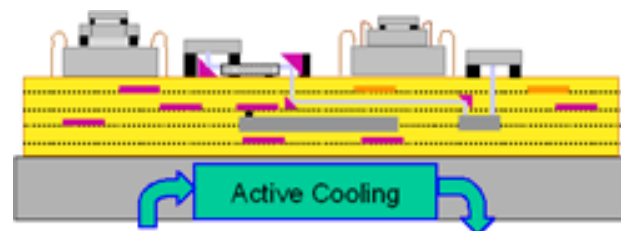
*A 32 layer
3-D package*

16 submodules, each
consisting of a
24 layer LTCC carrier with
16 rad-hard, flip-chip ICs
(8 per side)

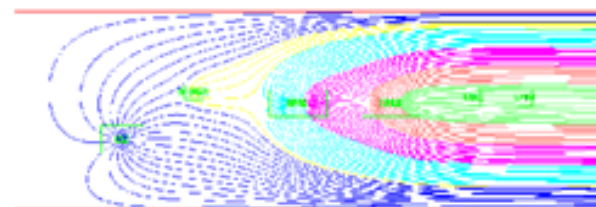


*Packaged
Microsystem*

- Advanced MCM Technology integrates high density interconnection for maximum performance in multi-chip modules.
- We apply thermal management through passive and active cooling technologies for high-power, low-volume applications.



*Active
cooling built
into MCM
technology*



*Model of
thermal
activity*

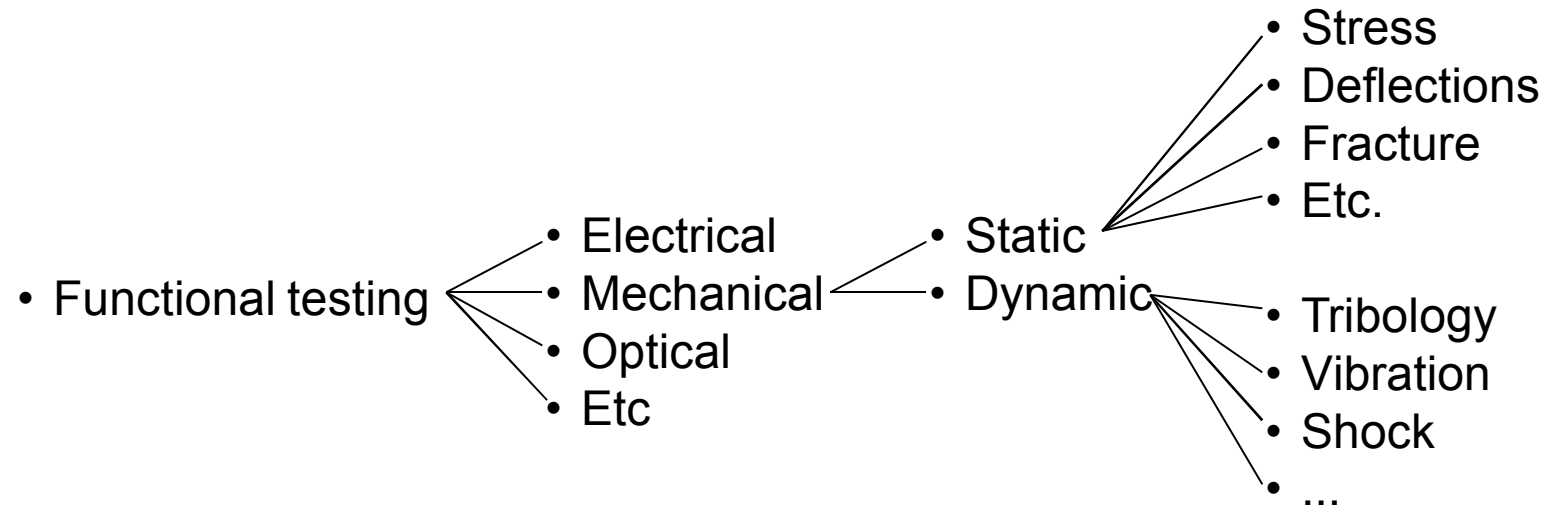
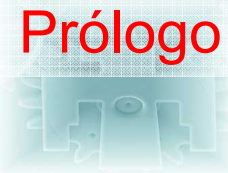


- Testing includes Functional Testing and Reliability Testing.
- Example of Reliability Testing: SHiMMeR (Sandia High Volume Measurement of Micromachine Reliability)



- Capable of testing a wide variety of device types.
 - Optical and electrical inspection
 - Can halt the actuation signal immediately after a device has failed.
- The environments can be air or nitrogen, controllable up to 65% RH and at ambient temperature.
- SHiMMeR II has the added capability of stress testing at higher temperatures through the use of resistive strips under the packages.

Shock and Vibration responses are important in MEMS



- The rest of this presentation will illustrate vibration and shock testing and modeling.

Case study 1: Mechanical Rebounds in Radio- Frequency (RF) MEMS

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PHYSICAL
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Waveform design for pulse-and-hold electrostatic actuation in MEMS

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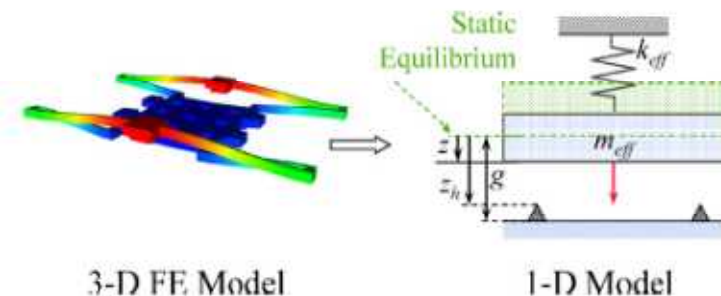
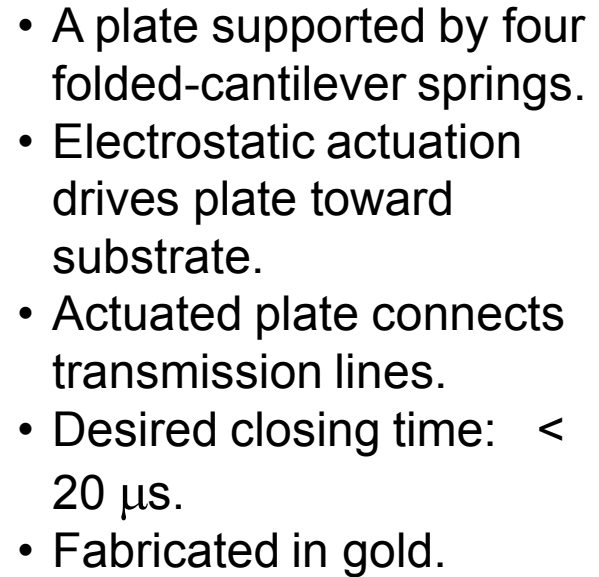
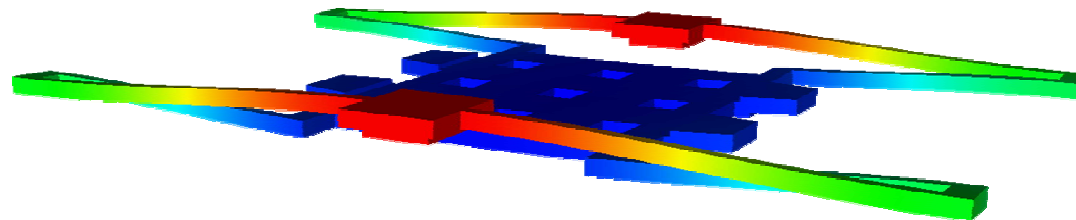
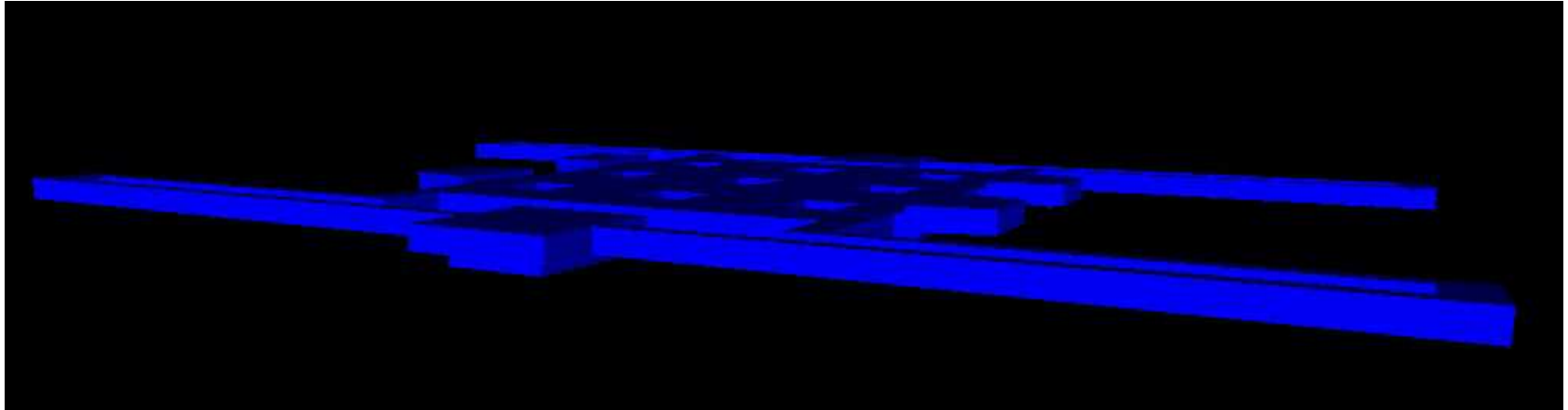


Fig. 5. Equivalence between 3-D FEM and 1-D model.

Rebotes Mecánicos en RF MEMS



- 

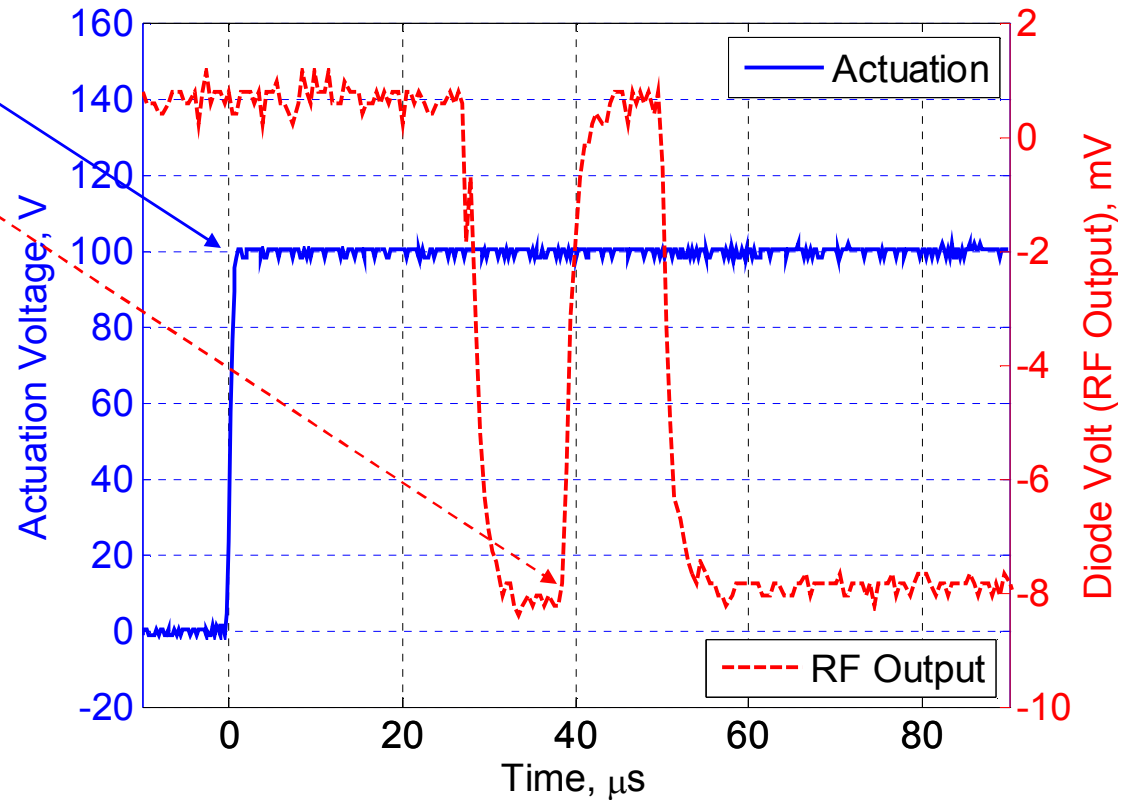


Energized position: plate down.

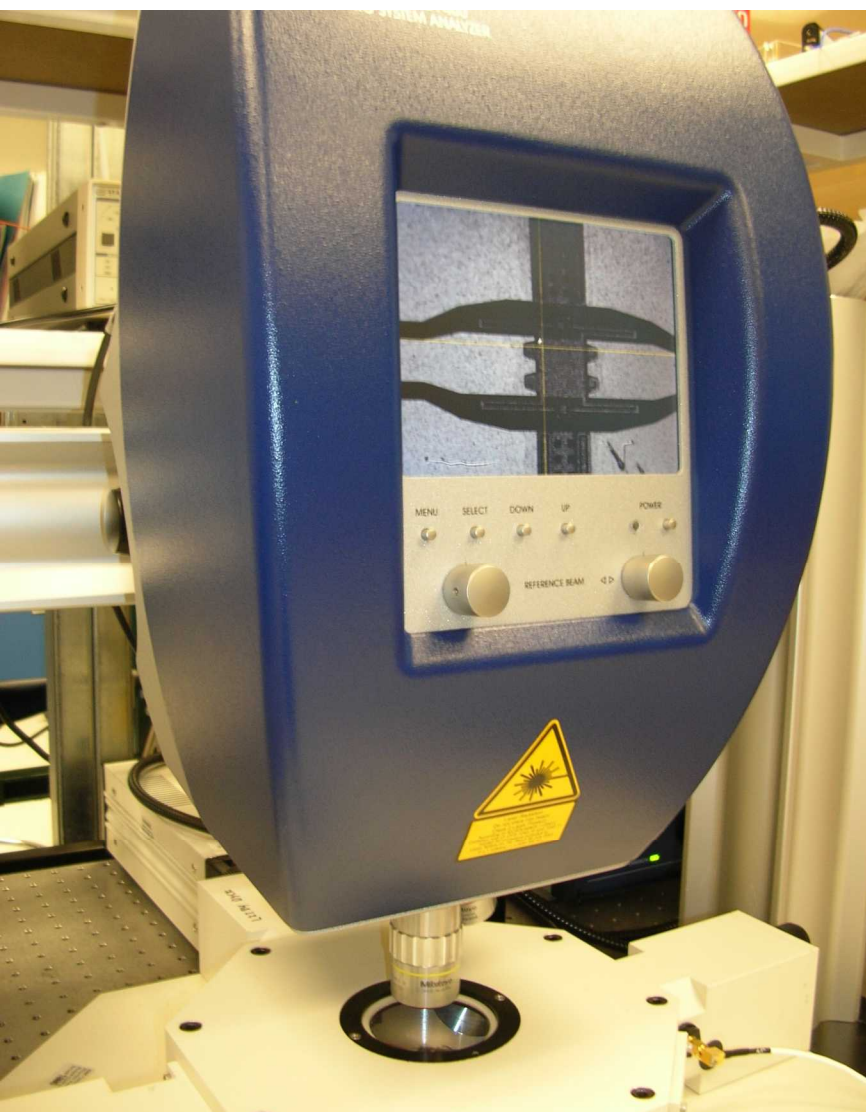
- **De-energizing**: Structural springs provide restoring force.

Step Actuation and Bouncing

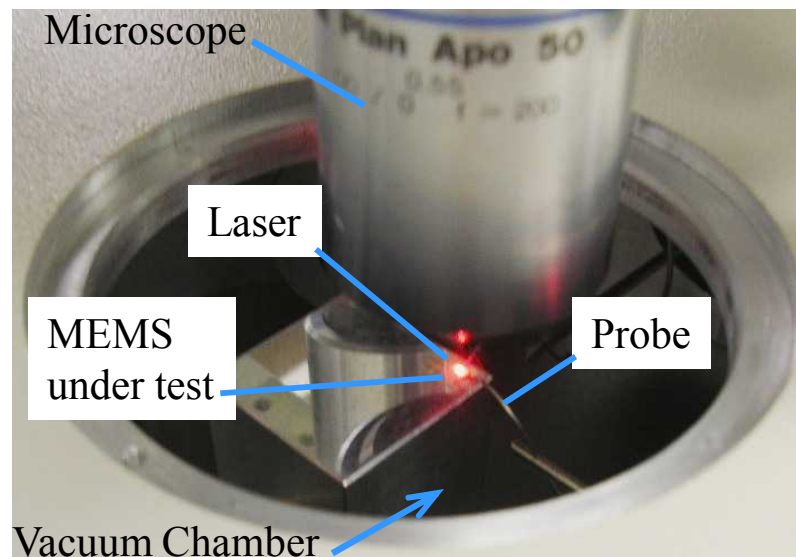
- Original actuation: **step voltage** to close switch.
- Problem: switch **bouncing** caused
 - Interruption of contact
 - Switch damage
 - Low life-cycle
- Changing the height of the step voltage did not reduce bouncing.



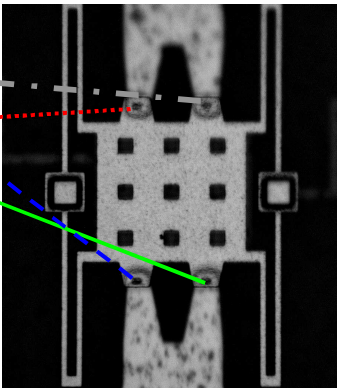
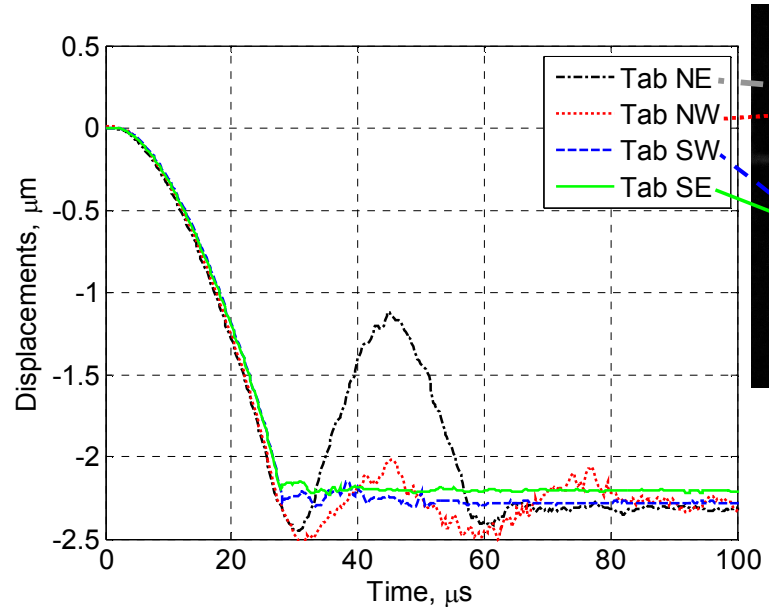
➡ Needs a closer look at the structural dynamics.



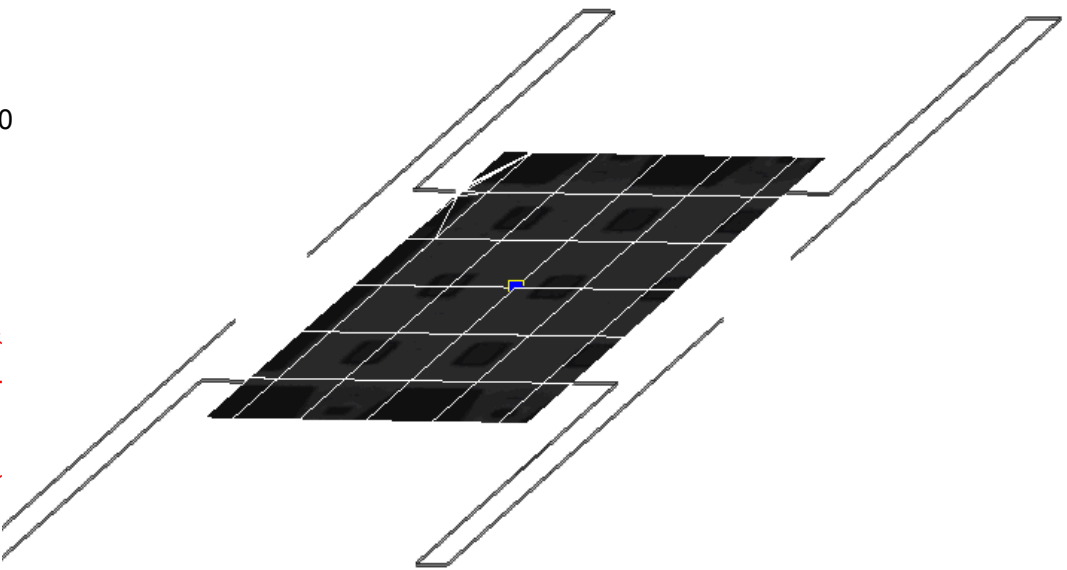
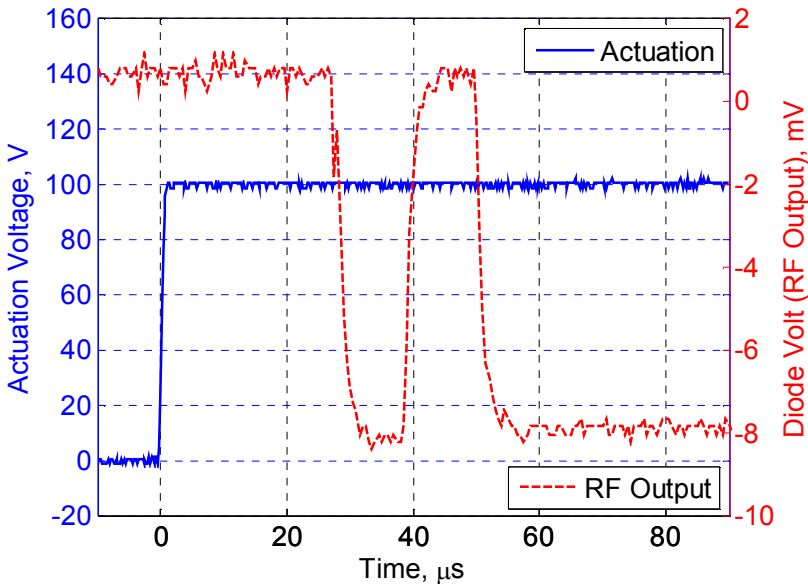
- Laser Doppler vibrometer (LDV) in optical train of microscope.
- LDV measures out-of-plane motion of the switch.
- Laser spot has $\sim 2 \mu\text{m}$ diameter.
- Measures 110 points on the switch.



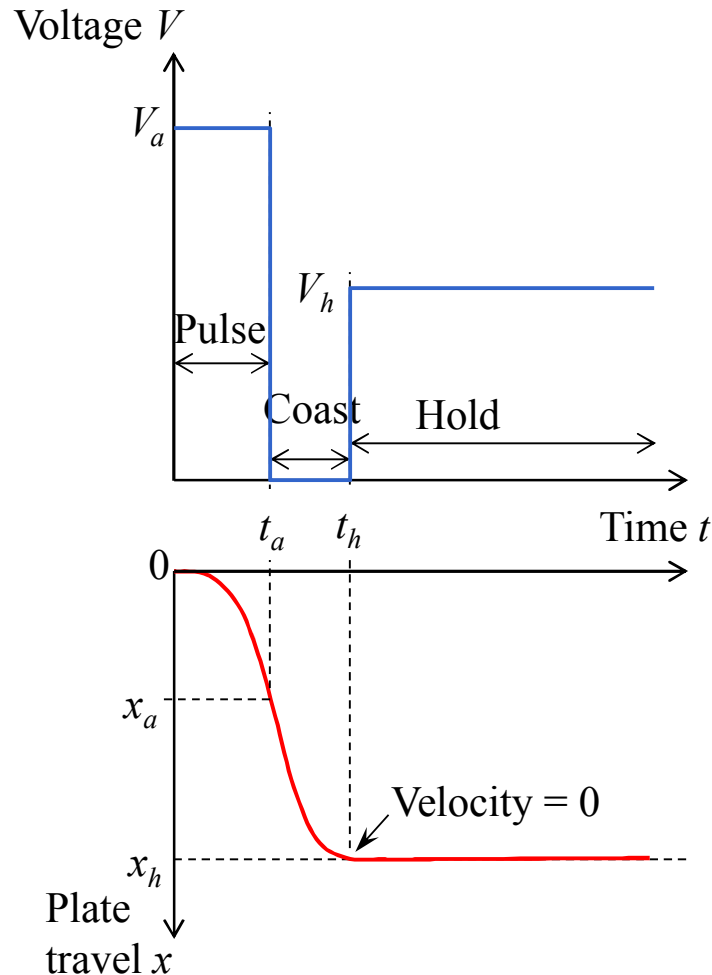
Mechanical Rebound Problem



Switch bouncing is caused by mechanical rebound.



Soft Landing Calculation



- Zero velocity (zero kinetic energy) desired at displacement x_h .
- Voltage and $F_{Electrostatic}$ are zero after
- Determine length of actuation pulse:

$$x(t_a) = x_a$$

Energy of spring-mass system
when m_{eff} displaces x_h

=

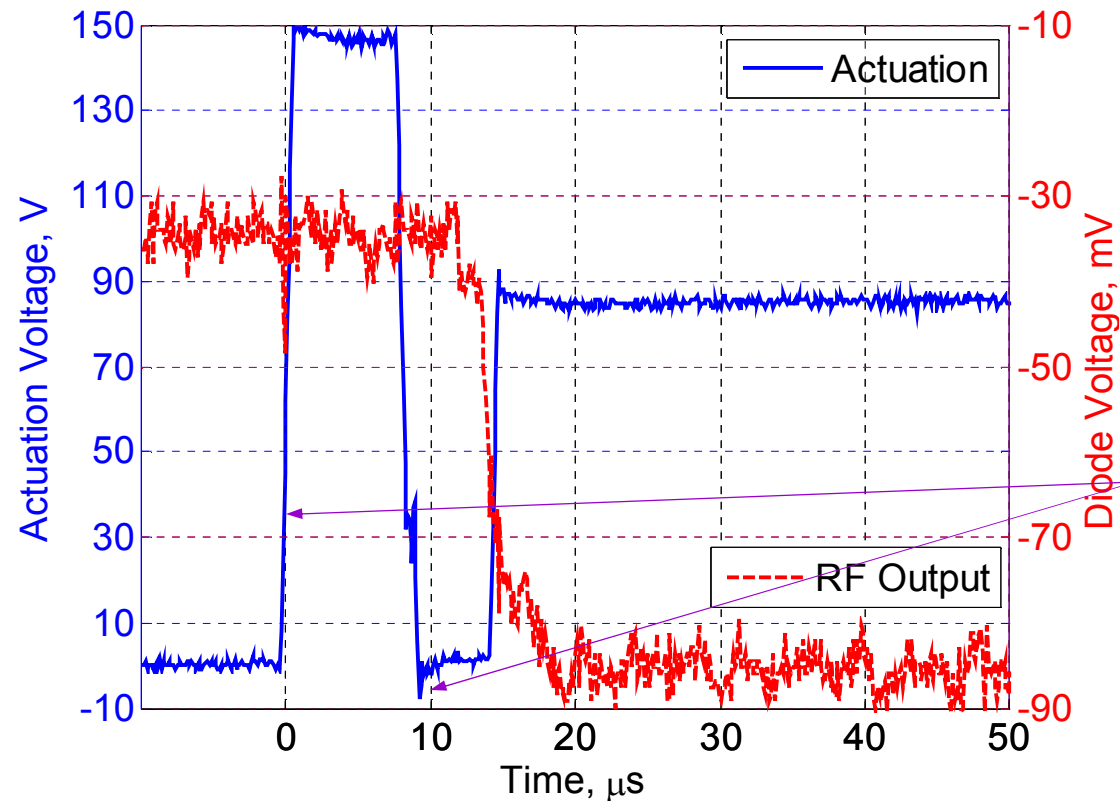
Work done on system by

$F_{Electrostatic}$

$$\frac{k_{eff} x_h^2}{2} = \int_0^{x_a} F_{Electrostatic} dx$$

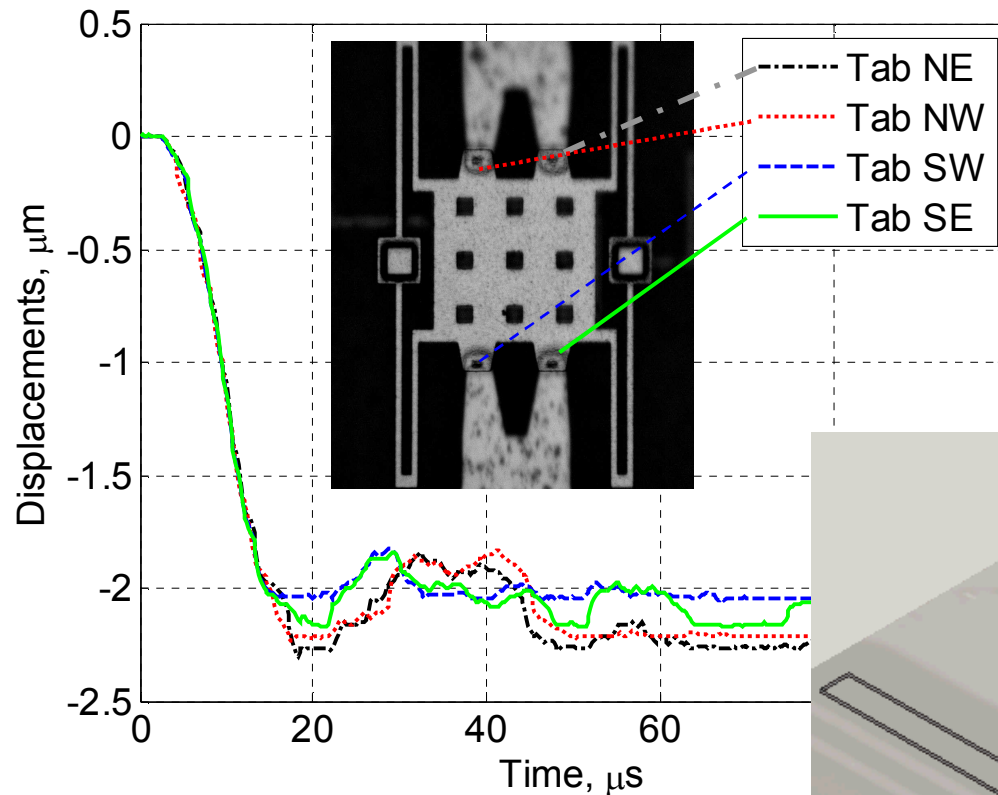
- Solve for x_a .
- Iteratively solve Equation of Motion to find time t_a .

Soft-landing Waveform Based on Model

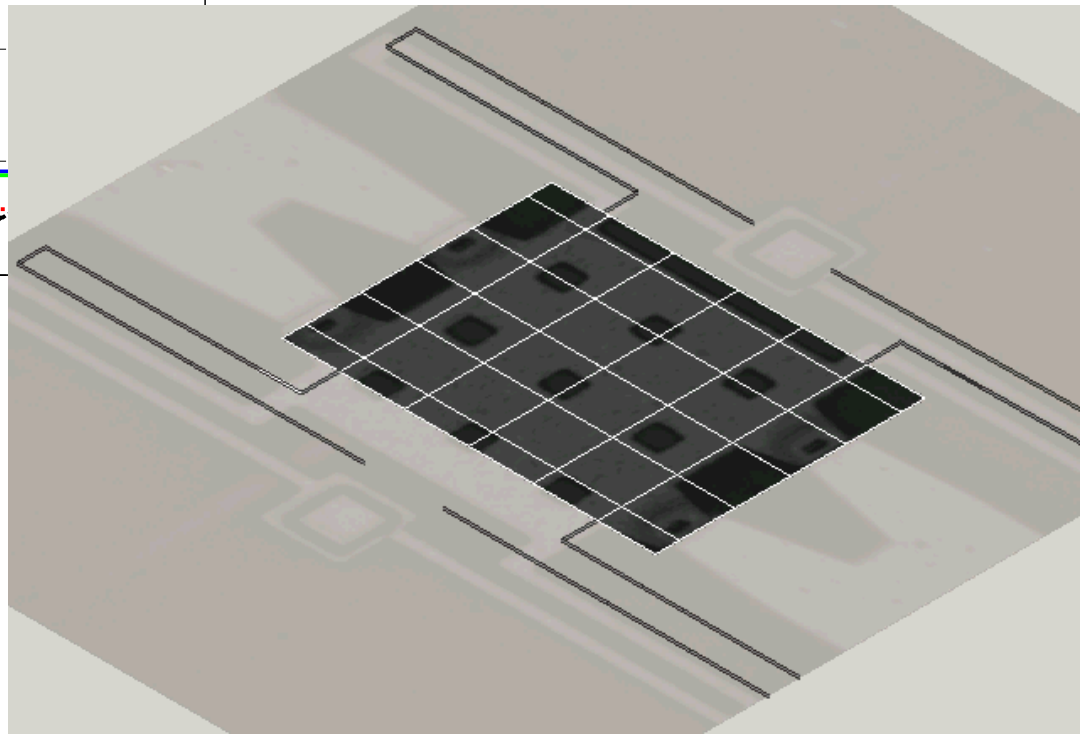


- Soft landing waveform generated from 1D effective model.
- 150 V, 9.6 μ s pulse.
- Coast for 4.7 μ s.
- 85 V hold voltage.
- Infinite slope is not implementable:
 - function generator time resolution is 50ns.
 - amplifier slew rate < 1MV/s.
- Overshoot appeared to affect switch bounce.

Soft Landing with Rectangular Waveform

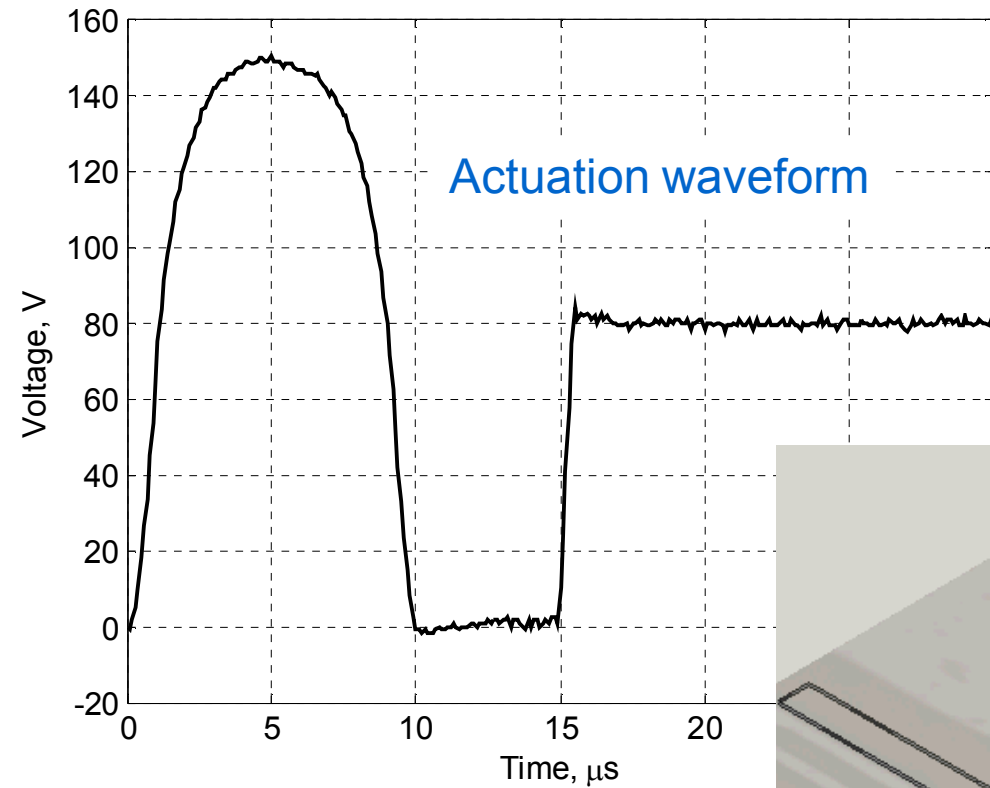


- Improvement over step waveform.

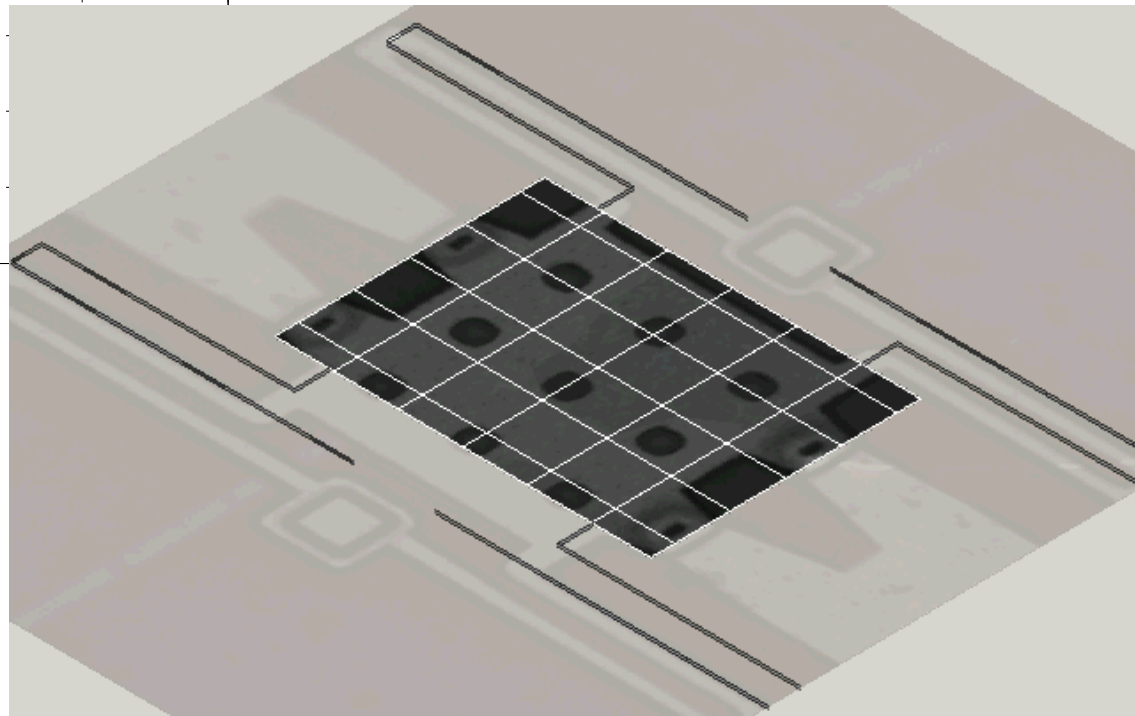


- Response sensitive to timing.
 - Pulse width
 - Start time of hold voltage
- Function generator resolution prevents exact timing.

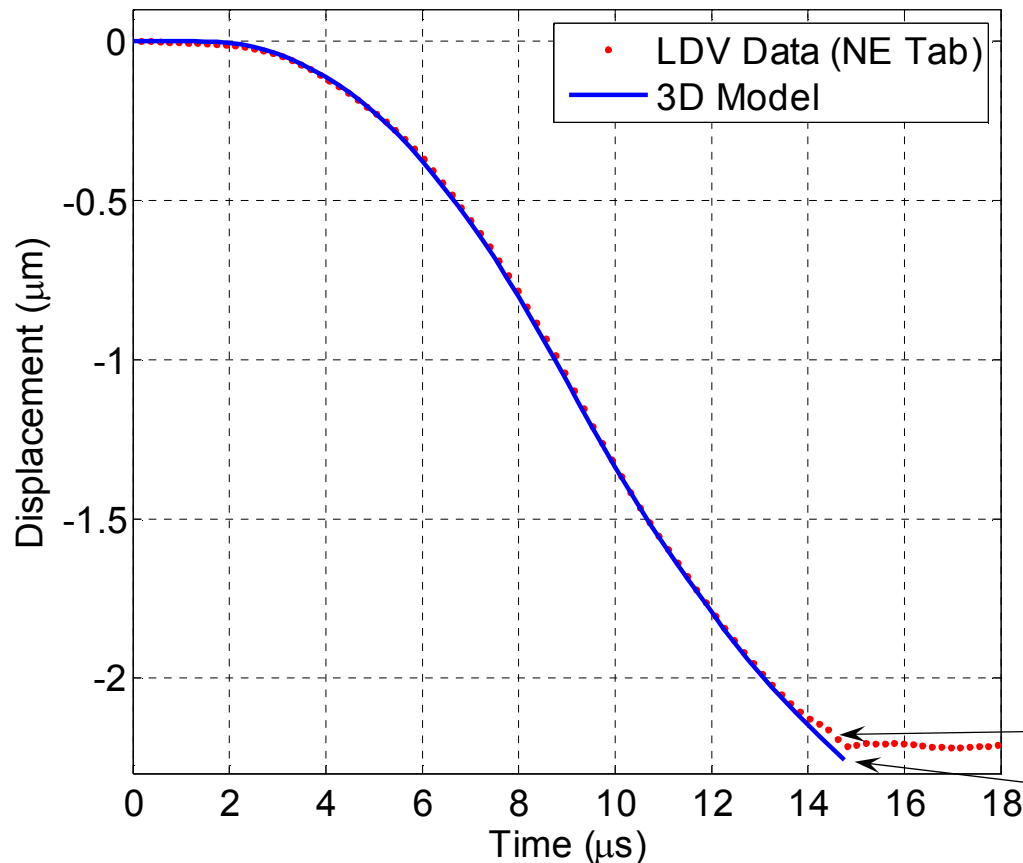
Rounded Waveform



Displacement vs. time



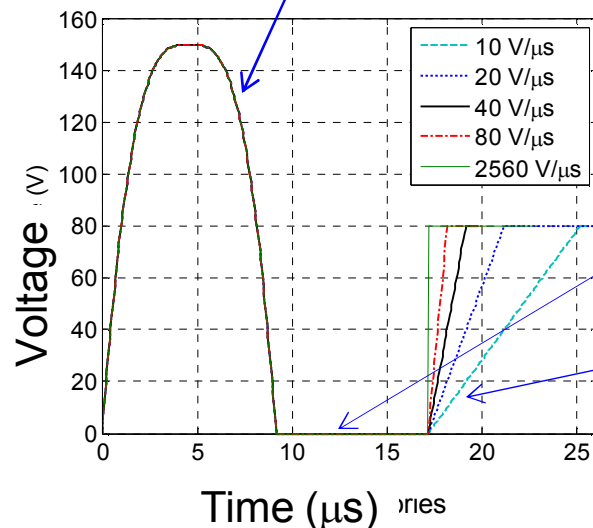
3D Model with Rounded Waveform



- Model prediction compared well with switch displacement with rounded waveform.
- Provided experimental validation of the model.
- Gas damping effect
 - Is neglected in the model.
 - Significant when squeezed gap is small.
 - May result in discrepancy.
 - May increase tolerance to non-zero landing speed.

Conclusions on RF MEMS Rebounds

- The high-fidelity 3-D finite element model captured mechanical dynamics of RF MEMS switch, as shown by test data.
- The calibrated single-degree-of-freedom model is effective in designing waveform that resulted in zero-velocity contact.
- Experimental refinement was needed in ensuring soft landing.
- Integrated numerical-and-experimental technique is successful in eliminating bouncing of the switch.
- The rounded waveform appears to result in softer landing and shorter closing time compared to the rectangular and trapezoidal waveform.



- If some low residual landing speed is acceptable, then some variation in coast time and hold voltage slope can be tolerated.

Case study 2: Gas Damping in MEMS

IOP Publishing

JOURNAL OF MICROMECHANICS AND MICROENGINEERING

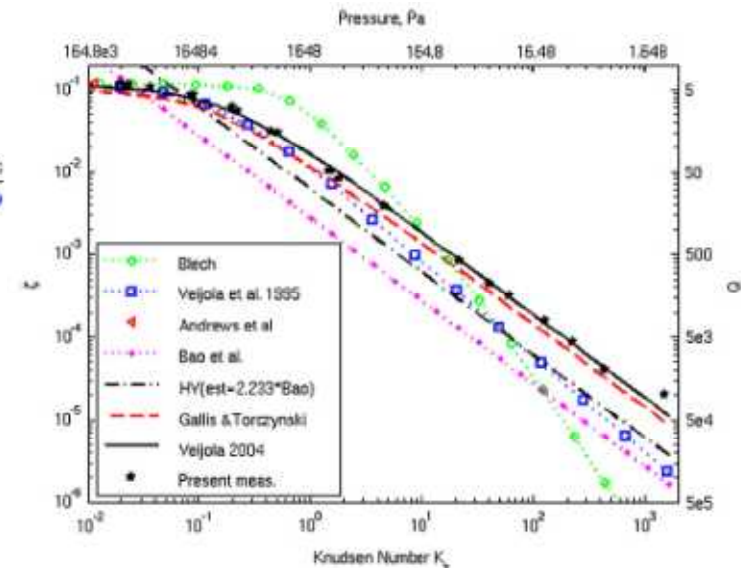
J. Micromech. Microeng. 17 (2007) 2231–2240

doi:10.1088/0960-1317/17/11/009

Squeeze-film damping in the free molecular regime: model validation and measurement on a MEMS

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Gas damping is important in MEMS.

Motivation:

- Many micro/nano devices need high Q factor. Examples abound in
 - MEMS switches need high speed (high Q).
 - Resonant cantilever sensors need high responses.
 - MEMS gyroscopes.
 - MEMS accelerometers need controlled damping.
- Damping can reduce Q from several hundred thousands to below ten.
- Squeeze-film damping determines the dynamics of plates moving a few microns above the substrate.
- Continuum models are not known to be valid in rarefied (free molecule) regime.
- Molecular-dynamics-based models for predicting squeezed-film damping give different results.
 - So which model should one use?
 - Need experimental validation!
- Published experimental data were obtained for squeeze-film damping on *flexible* structures. Have been used to validate theory derived for *rigid* structures.

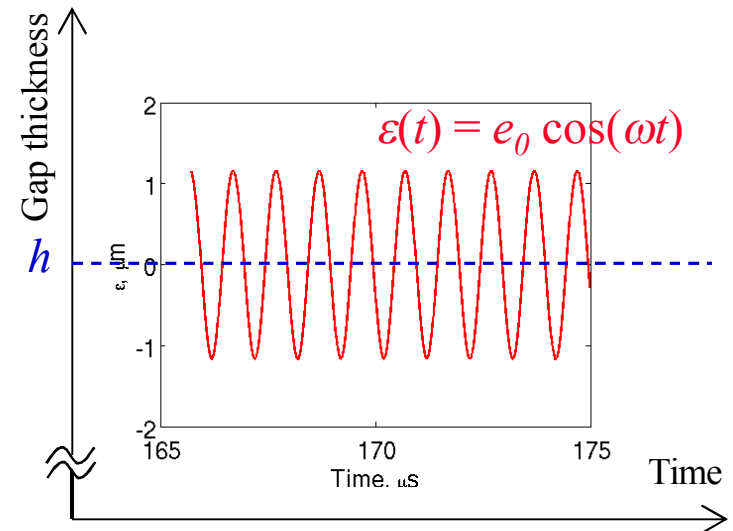
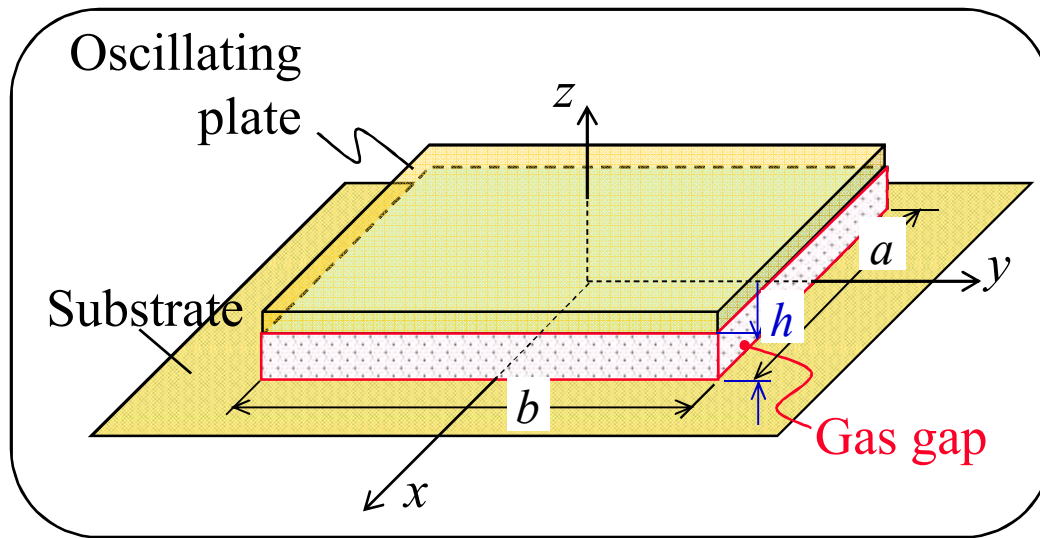
Objective:

- Provide experimental validation to squeezed-film damping models for rigid plates.

Squeezed fluid damps oscillation.

Amortiguación
de vibración
por gas

Plate oscillates at frequency ω .



The squeezed fluid between the plate and the substrate creates damping forces on the plate.

For sensors, rigid plate parallel to substrate, moving up and down, is preferred over flexible plates. [H. Seidel et al. 1990 *Sensors and Actuators*, **21** 312-315.]

Knudsen number determines damping regime

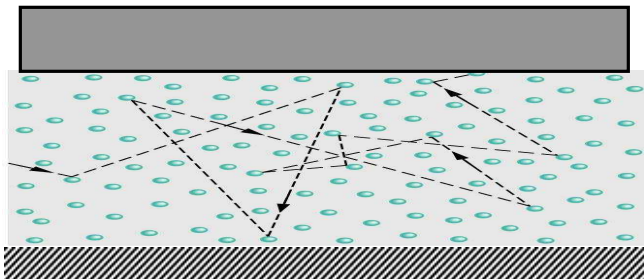
Amortiguación
de vibración
por gas

- Knudsen number $K_s = 1.016$ mean free path/(gap size).

- Mean free path $\lambda = \frac{\mu}{P} \sqrt{\frac{2RT}{m_m}}$
 μ = viscosity, Pa.s
 R = universal gas constant, J/(mol.K)
 T = temperature, K
 m_m = molecular mass, kg/mol

- Continuum models, eg. Are based on spatial derivatives.

- Do they apply when the gap is comparable to, or smaller than the mean free path?



Many researchers say no. Molecular-dynamics-based models are needed.

We need experimental data.

<http://www.phas.ucalgary.ca/~annlisen/teaching/Phys223/PHYS223-LECT34.html>

Published molecular models still could not explain published measured damping.

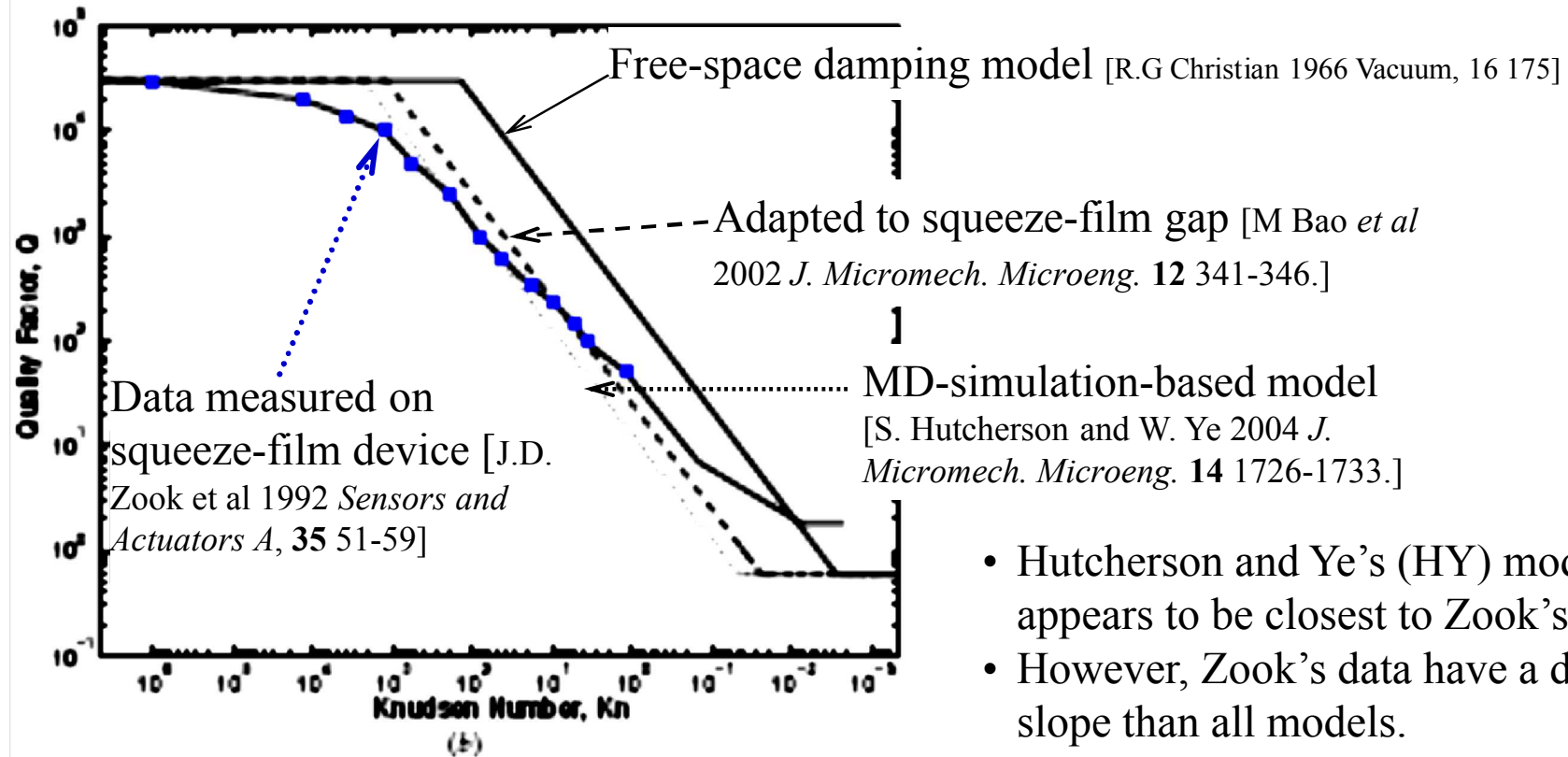


Figure 6. Quality factor results: (a) pressure versus quality factor, (b) Knudsen number versus quality factor.

- Hutcherson and Ye's (HY) model appears to be closest to Zook's data.
- However, Zook's data have a different slope than all models.
- Zook's geometry and test conditions are not well known or modeled.

We need

- A model that is validated by measured data.
- Measurement data with better characterized test device and conditions.

“Molecular” models could not be validated with available data. Try continuum models

- Forces on moving plate from gas layer can be obtained from the linearized

Reynolds equation

$$\frac{Ph^2}{12\mu} \nabla^2 \left(\frac{p}{P} \right) - \frac{\partial}{\partial t} \left(\frac{p}{P} \right) = \frac{\partial}{\partial t} \left(\frac{z}{h} \right)$$

P = ambient pressure, Pa

h = gap size, m

μ = viscosity, Pa s

p = pressure at (x,y) , Pa

t = time, s

Assumptions:

1. Rigid plate
2. Small gap
3. Small displacement
4. Small pressure variation
5. Isothermal process
6. Small molecular mean free path

- Assumptions in the continuum models:

•Blech’s model

(7. On edges, pressure is assumed to be ambient pressure.

8. Inertia of fluid is neglected)

•Andrews et al.’s limit

(9. Zero Knudsen number limit of Blech’s)

•Veijola’s model

Free from 7 and 8.

Blech's model was derived for continuum regime, low Knudsen number.

- Blech's damping coefficient

$$c^{Blech}(\omega) = \frac{768}{\pi^6} \frac{a^3 b}{h^3} \mu \sum_{m,n \text{ odd}} \frac{m^2 + n^2 (a/b)^2}{m^2 n^2 [m^2 + n^2 (a/b)^2]^2 + \sigma^2 / \pi^4}$$

- Depends on the **squeeze number**

$$\sigma = 12\mu \left(\frac{a}{h_m} \right)^2 \left(\frac{\omega}{P} \right)$$

- For low squeeze numbers, $\sigma \ll \pi^2$

a = plate width, m
 b = plate length, m
 h = gap height, m
 P = ambient pressure, Pa
 μ = viscosity, Pa s
 ω = frequency, rad/s

$$c^{Andrews} = 0.42(ab)^2 \mu / h^3$$

(Andrews et al's model).

- Blech's typical applicable range: $\mu = 1.82(10)^{-5} \text{Pa.s}$; $a = 144 \mu\text{m}$; $h = 4.5 \mu\text{m}$.
in atmosphere $P=9.3(10)^4 \text{Pa}$: $\sigma < 1$ for

$$\omega / (2\pi) < 70 \text{kHz}$$

Veijola's model accounts for fluid inertia.

- Taking into account rarefaction and the inertia of the gas flowing in and out of the gap, Veijola (2004) modified Reynolds equation into

$$\frac{\partial}{\partial x} \left(\frac{\rho h^3}{12\mu} Q_{pr} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\rho h^3}{12\mu} Q_{pr} \frac{\partial p}{\partial y} \right) = \frac{\partial \rho h}{\partial t}$$

h = gap size, m
 p = pressure at (x,y) , Pa
 t = time, s
 μ = viscosity, Pa s
 ρ = density, kg/m³

- If the gap oscillation is $\varepsilon(t) = e_0 \exp(j\omega t)$, then the damping force complex amplitude is

$$F^{Veij}(\omega) = j\omega e_0 \Phi(\omega)$$

$$\Phi(\omega) = \sum_{m=1,3,\dots}^M \sum_{n=1,3,\dots}^N \frac{1}{Q_{pr} G_{mn} + j\omega C_{mn}}$$

$$Q_{pr} = \sum_{k=1,3,\dots} \frac{1 + 6K_s}{\frac{k^4 \pi^4}{96} + j\omega \frac{k^2 \pi^2 \rho h^2 (1 + 10K_s + 30K_s^2)}{96\mu(1 + 6K_s)}}$$

$$C_{mn} = \frac{\pi^4 h (mn)^2}{64 a b n_\gamma P}$$

$$G_{mn} = \frac{\pi^6 h^3 (mn)^2}{768 \mu a b} \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right)$$

Knudsen number

$$K_s = 1.016 \lambda / h$$

λ = mean free path, m

a = width, m
 b = length, m
 e_0 = amplitude, m
 j = $\sqrt{-1}$
 n_γ = 1 for isothermal,
 (= c_p/c_v for adiabatic).
 P = ambient pressure, Pa
 μ = viscosity, Pa s
 ω = frequency, rad/s
 ρ = gas mass density, kg/m³

Gallis and Torczynski's (GT) model combines Reynolds equation with molecular dynamics.

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de vibración
por gas

Is a Direct Simulation Monte Carlo (DSMC) method.

Instead of the trivial boundary conditions at the plate edges, GT introduced

$$P - p = \eta G (\hat{\mathbf{n}} \cdot \nabla p) + \zeta \left(\frac{12\mu U}{G} \right) \left(1 + \chi \frac{6\Lambda}{G} \right)^{-1}$$

DSMC simulations were used to determine correlations for the gas-damping parameters

$$\eta = \frac{0.634 + 1.572(\Lambda/G)}{1 + 0.537(\Lambda/G)} \quad \chi = \frac{1 + 8.834(\Lambda/G)}{1 + 5.118(\Lambda/G)} \quad \zeta = \frac{0.445 + 11.20(\Lambda/G)}{1 + 5.510(\Lambda/G)}$$

G = gas film (gap) thickness. Λ/G is modified Knudsen number $\Lambda = \frac{2-\alpha}{\alpha} \lambda \quad 0 \leq \Lambda/G \leq 1$

α = accommodation coefficient. (For this test device $\alpha = 1$).

Sumali H, Torczynski JR, Epp DS and Gallis MA 2007 Experimental Validation of a Squeeze-Film Damping Model Based on Molecular Gas Dynamics *Proc. 2007 ASME International Design Engineering Technical Conference*.

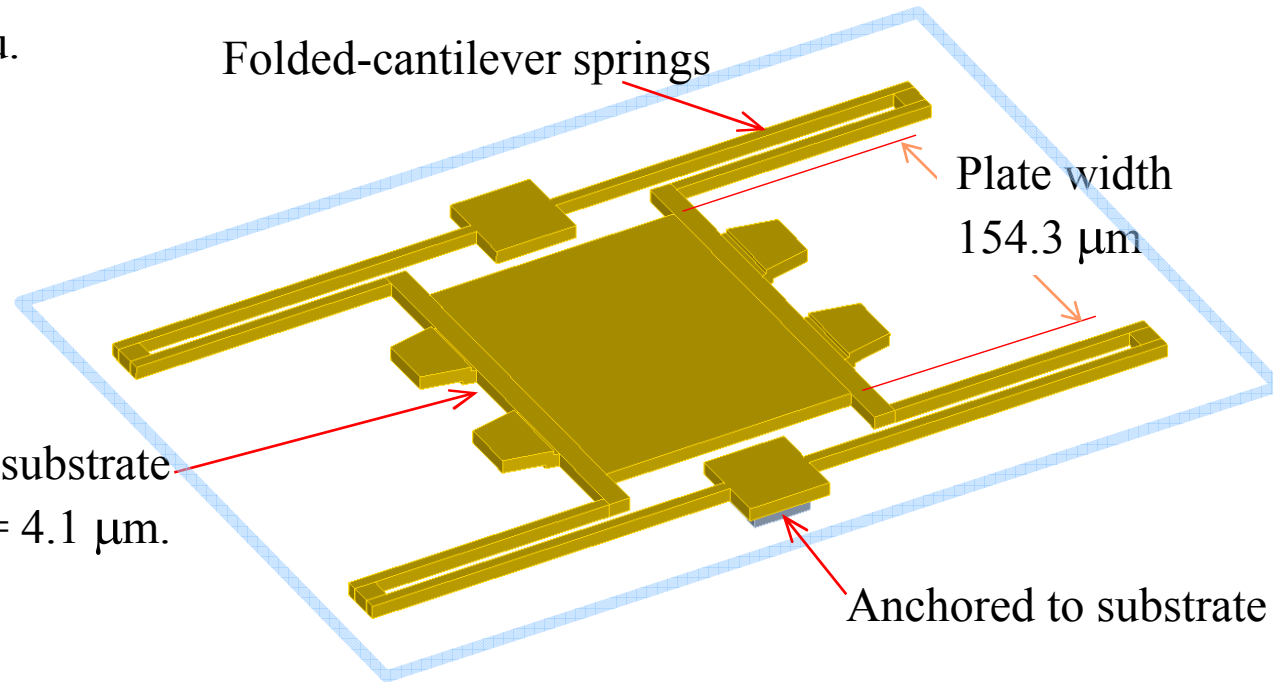
Present measurement was done on an oscillating plate.

- Structure is electro-plated Au.
- Thickness around $5.7 \mu\text{m}$.
- Substrate is alumina.

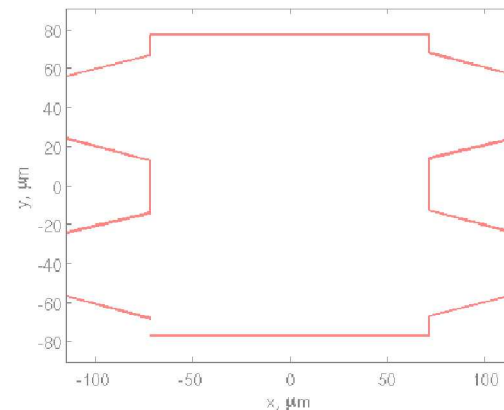
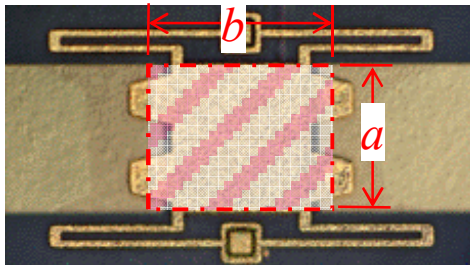
$$A = 29717(\mu\text{m})^2$$

$$a = 154.3 \mu\text{m}$$

Air gap between plate and substrate
Mean thickness = $4.1 \mu\text{m}$.

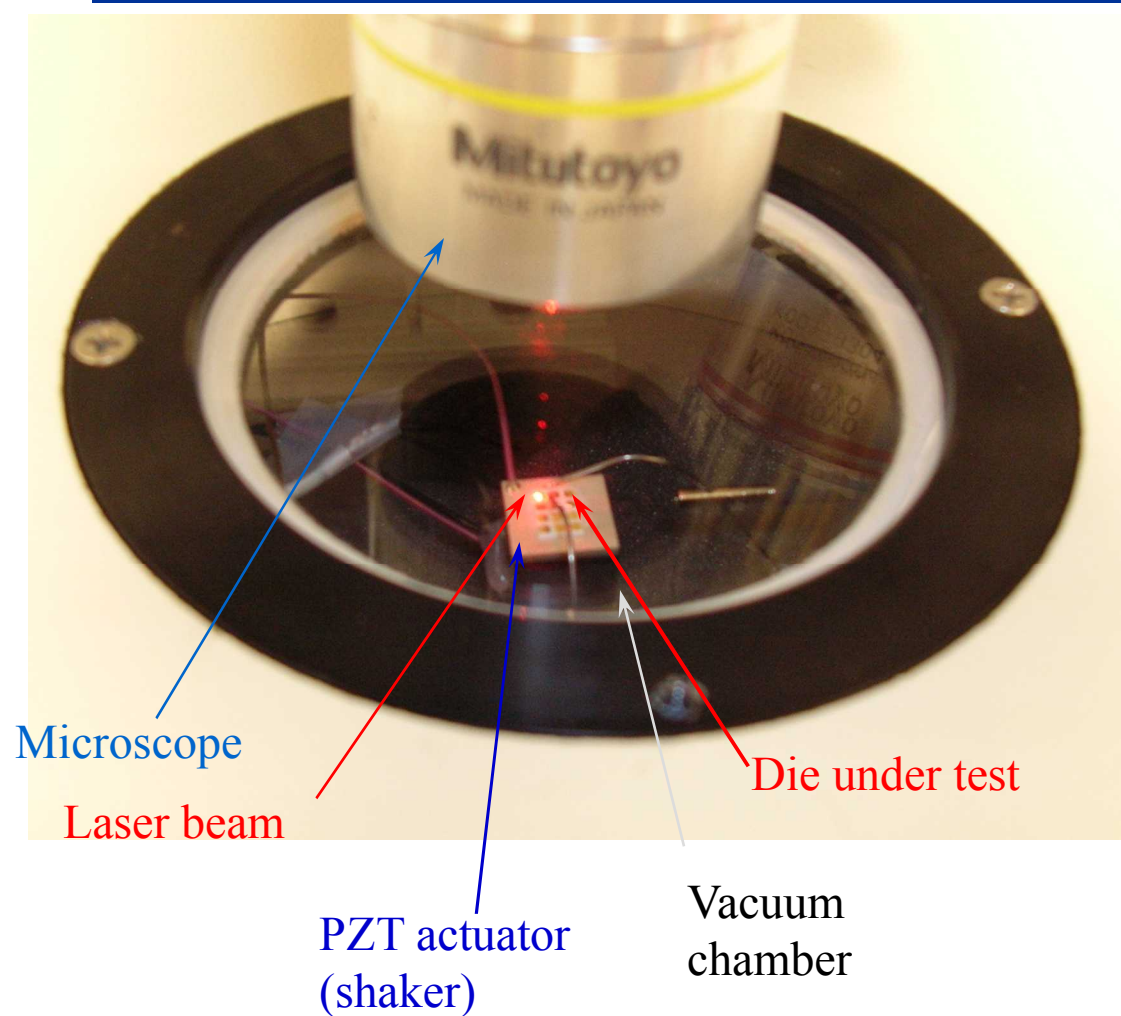


- Assumed width a and length b ,
where $ab = \text{true plate area}$.



Measurement uses LDV and vacuum chamber.

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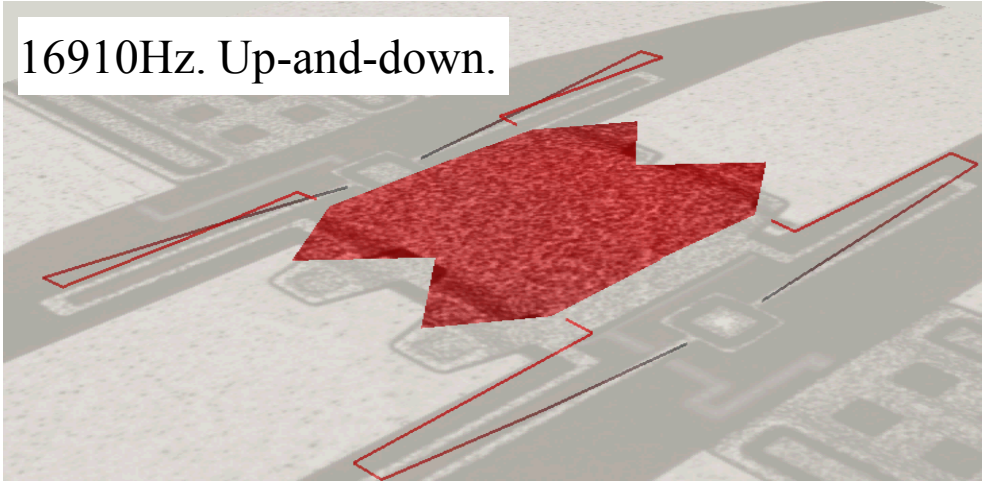
- Substrate (base) was shaken with piezoelectric actuator.
- Scanning Laser Doppler Vibrometer (LDV) measures velocities at base and at several points on MEMS under test.

Experimental modal analysis gives natural frequency, damping and mode shapes.

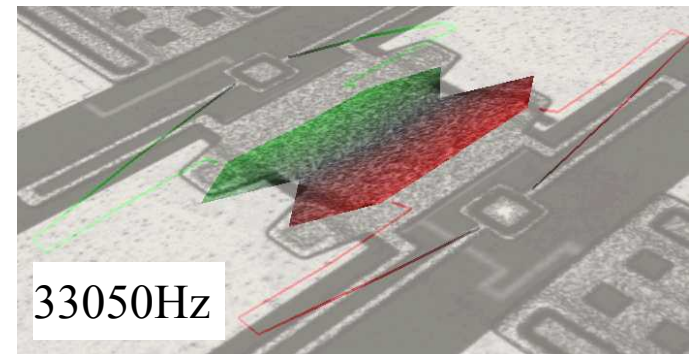
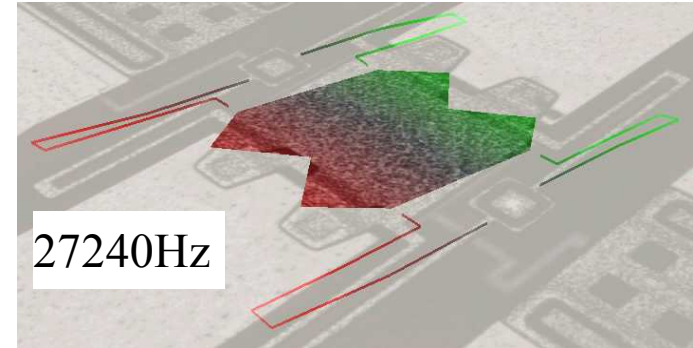
Amortiguación
de vibración
por gas

Measured deflection shape, first mode.

16910Hz. Up-and-down.

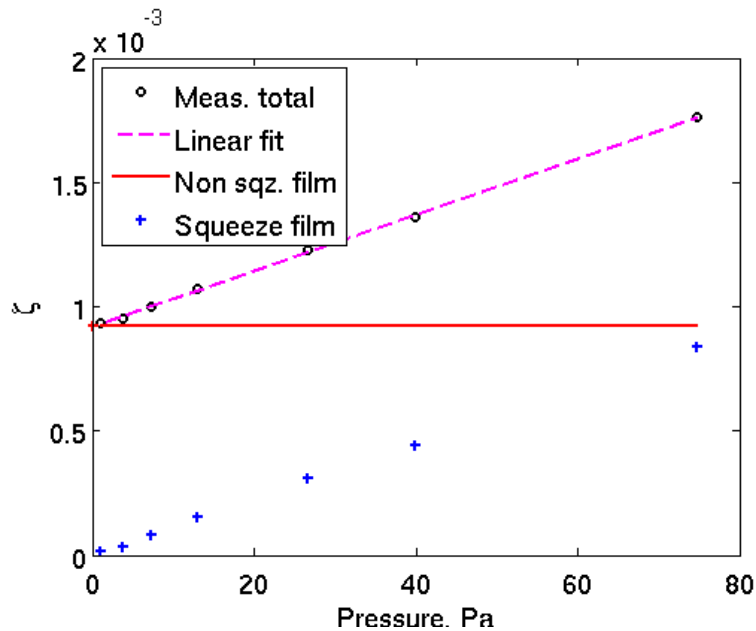


Higher modes are not considered.



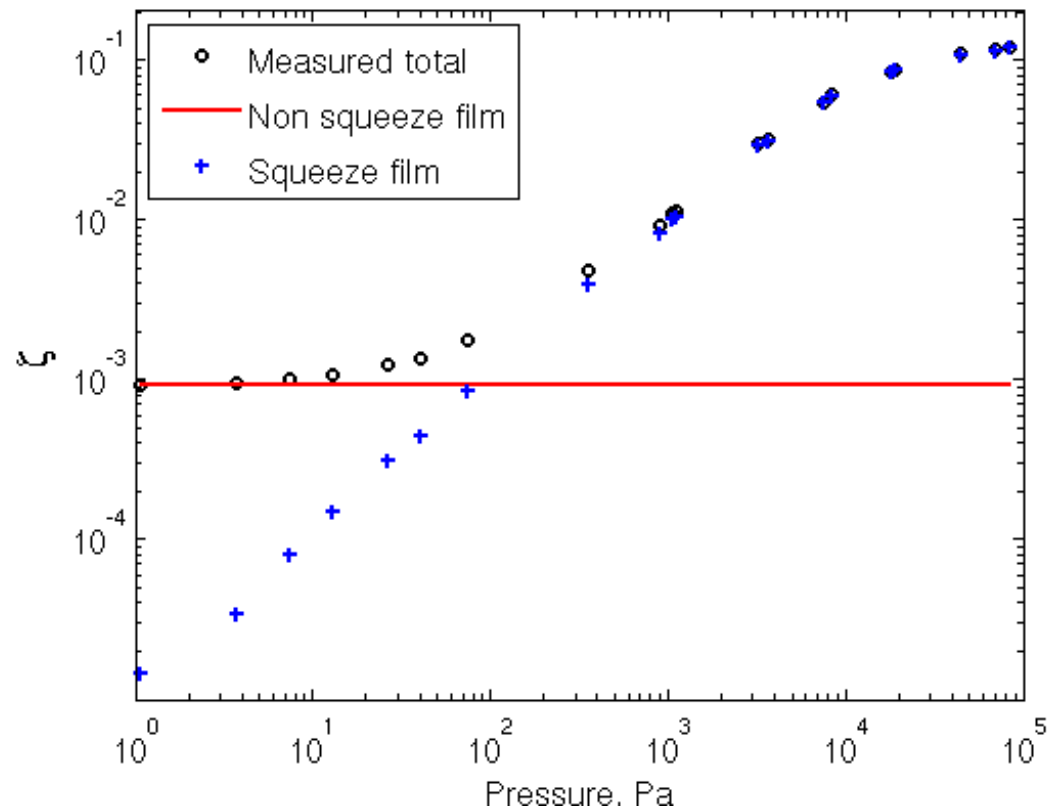
- Tests were repeated at different air pressures from atmospheric (640 Torr) to near-vacuum (<1 milliTorr).

Non-squeeze-film damping is estimated from zero-pressure asymptote.



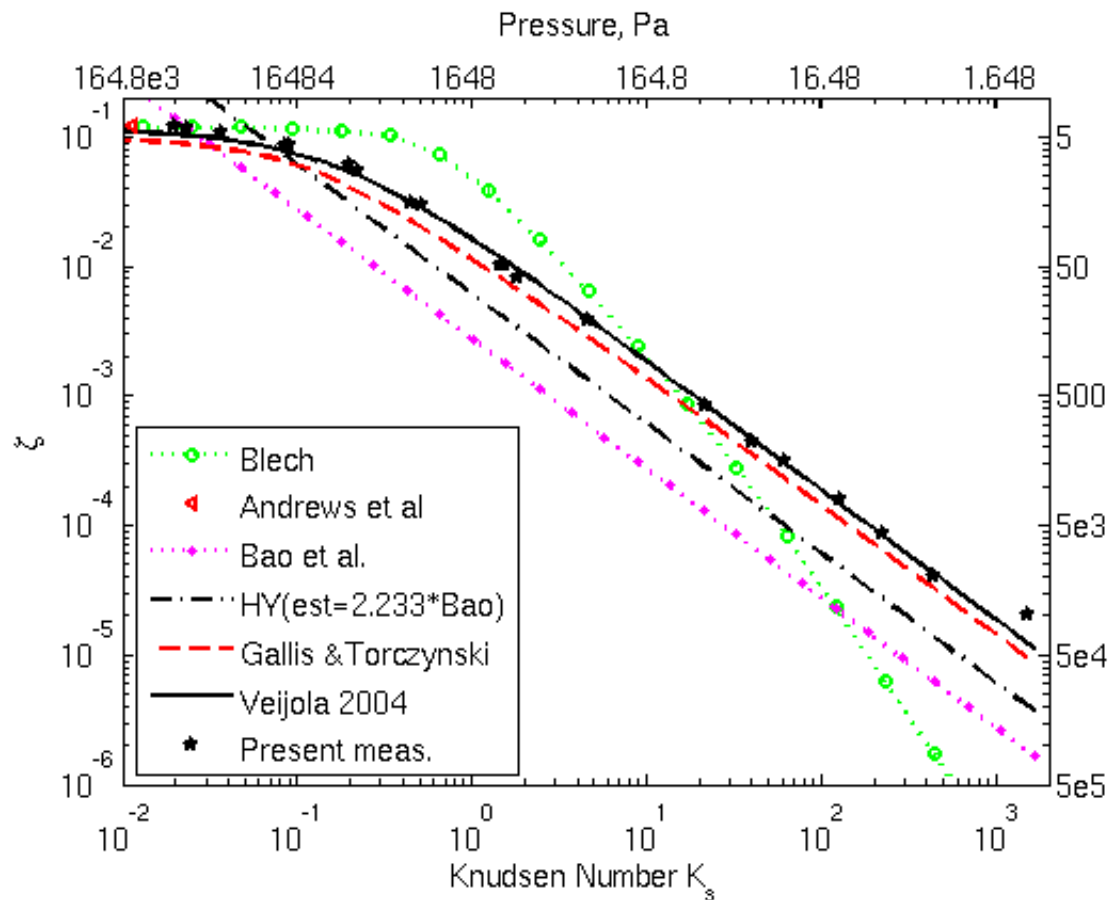
- At low pressures, Non-Squeeze-Film Damping (NSFD) is the dominant damping.
- Linear-fit total measured damping at a few lowest-pressures. The zero-pressure intercept is NSFD.

- To obtain squeeze-film damping from measured total damping, subtract NSFD from total measured damping.



Some models predict measured data very well.

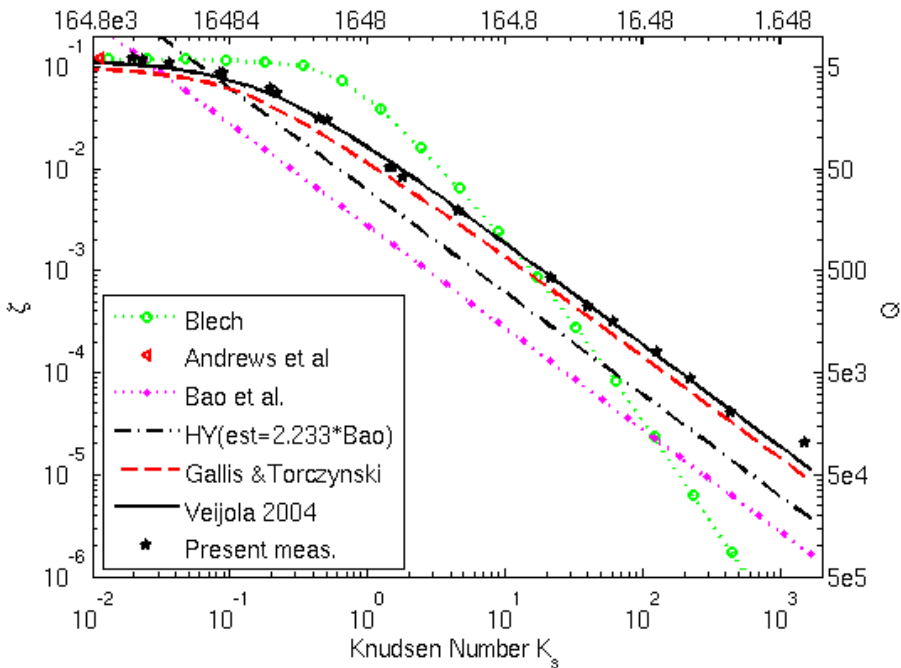
Amortiguación
de vibración
por gas



- Blech model was developed for low Knudsen numbers.
- Andrews et al's limit is accurate at low K_s .
- Literature¹ showed Bao et al's model to be more accurate after modification.
- HY curve in graph was estimated, not from Hutcherson-Ye's computationally extensive model.
- Gallis-Torczynski and Veijola's models agree well with test data.

¹Minikes A, Bucher I and Avivi G Damping of a micro-resonator torsion mirror in rarefied gas ambient *Journal of Micromechanics and Microengineering* 15 1762-9
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Thus, the test data suggest the following conclusions:



- On rigid plates with width $\sim 150 \mu\text{m}$, oscillating around $4.1 \mu\text{m}$ above the substrate, squeezed air film can cause large damping.
 - Non-molecular models are not necessarily less accurate than current molecular-based models.
 - For the conditions tested here, in atmospheric air the simplest model mentioned by Andrews et al. is as good as any more sophisticated models.
- $$c^{Andrews} = 0.42 A^2 \mu / h^3$$

- In the high squeeze number regime (low pressures or high frequencies), Veijola's model appears to match experimental data accurately.

Sensor Testing Examples

APPLIED PHYSICS LETTERS 92, 114102 (2008)

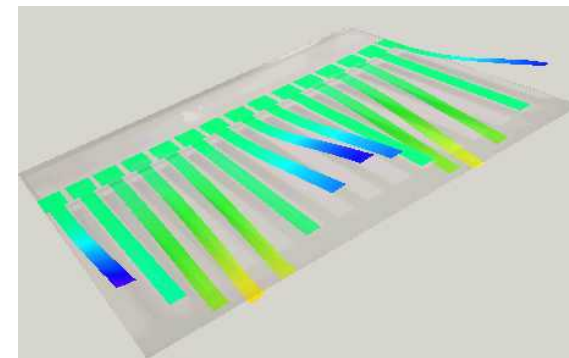
Highly sensitive mass detection and identification using vibration localization in coupled microcantilever arrays

Matthew Spletzer,¹ Arvind Raman,^{1,a)} Hartono Sumali,² and John P. Sullivan³

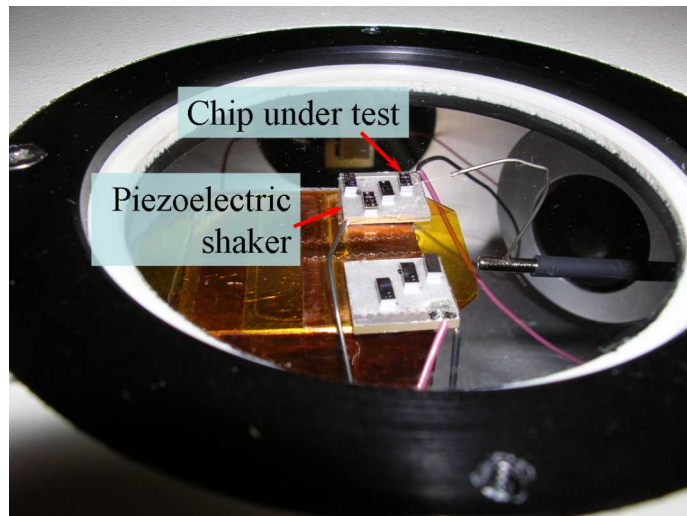
¹*School of Mechanical Engineering and the Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA*

²*Applied Mechanics Development Department, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

³*Center for Integrated Nanotechnology Science Department, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

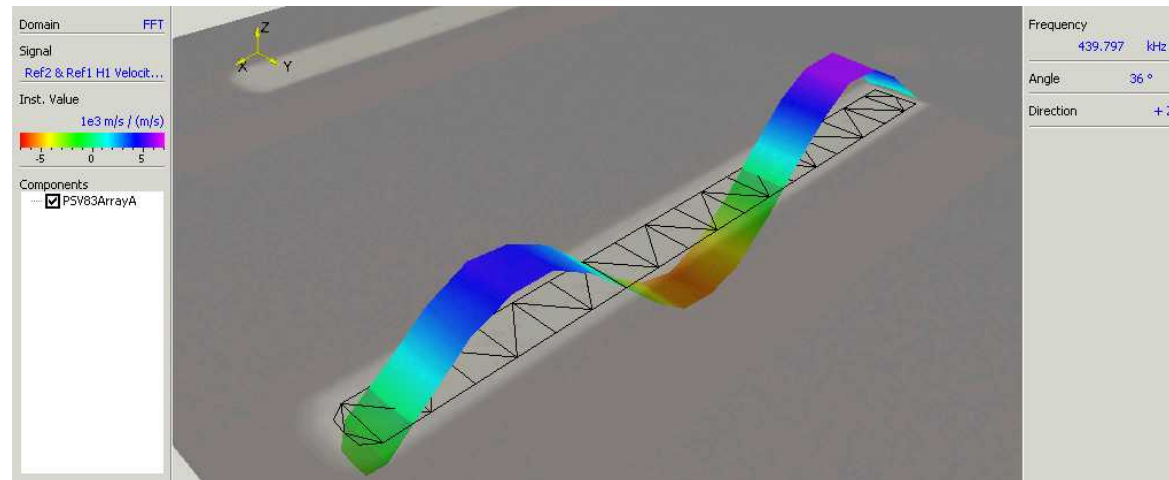


Laser Doppler Vibrometer measures the vibrations of an AFM cantilever probe

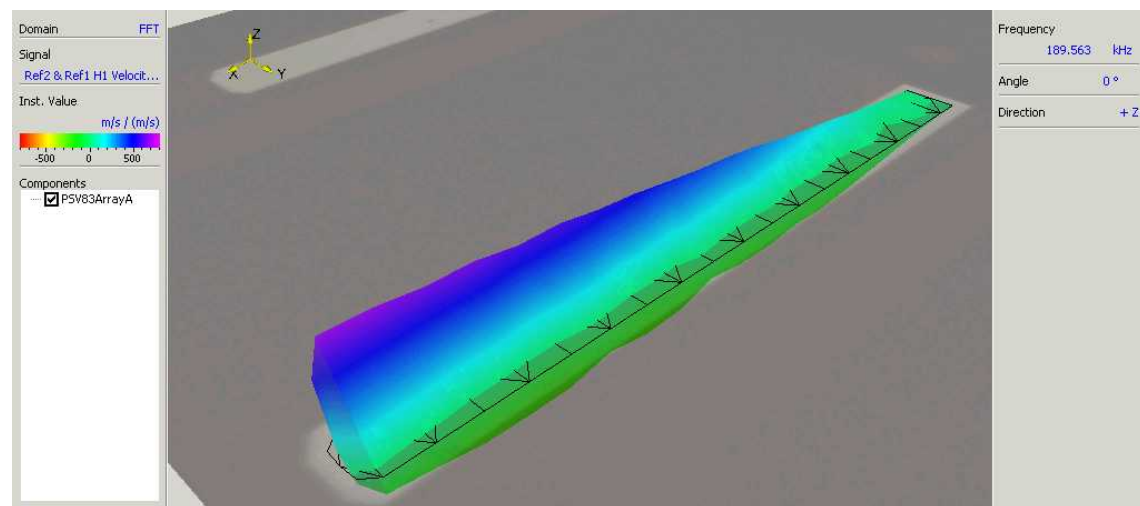


A bending mode, 440kHz

Measured with laser Doppler vibrometry, in a vacuum chamber.

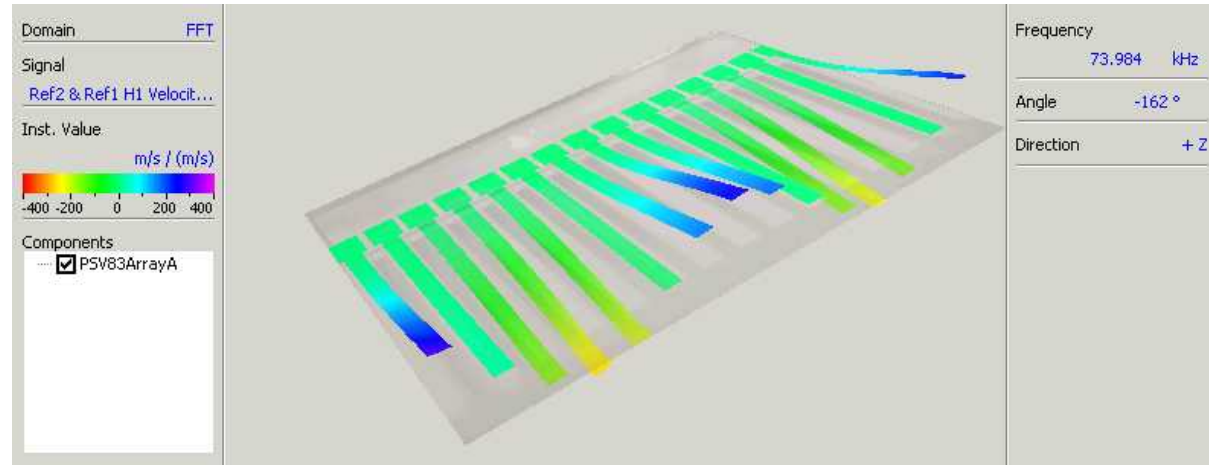


Torsion mode, 190kHz

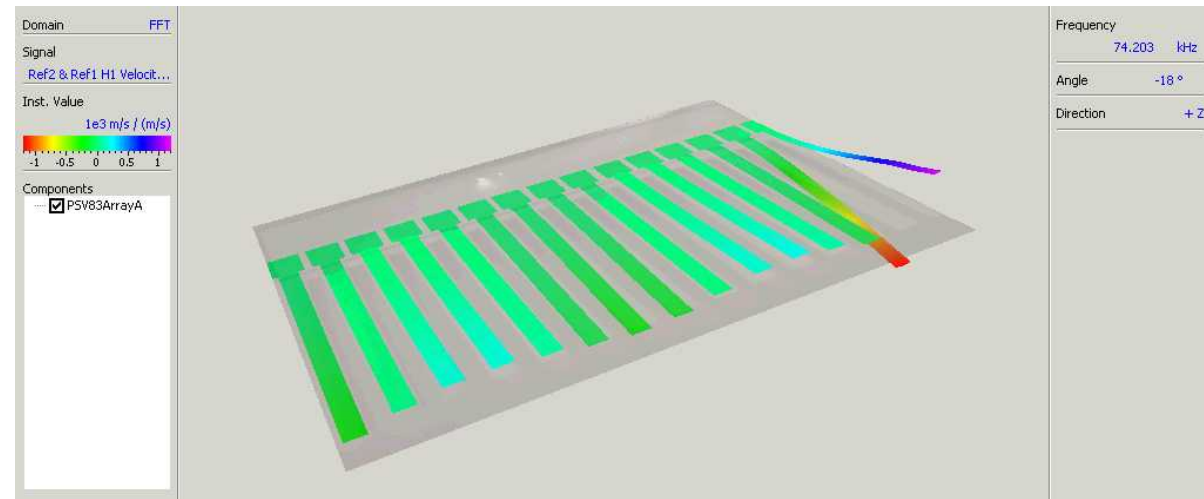


An array of micro cantilevers is capable of measuring 10 picogram of mass.

Vibration mode shape of
array without mass.



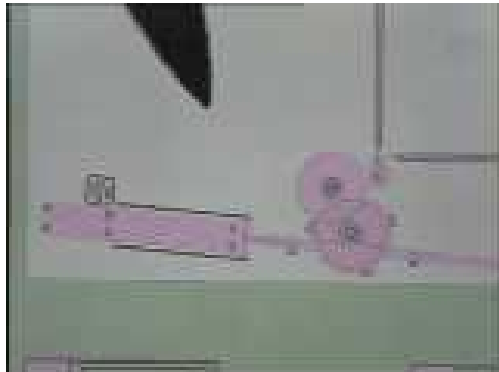
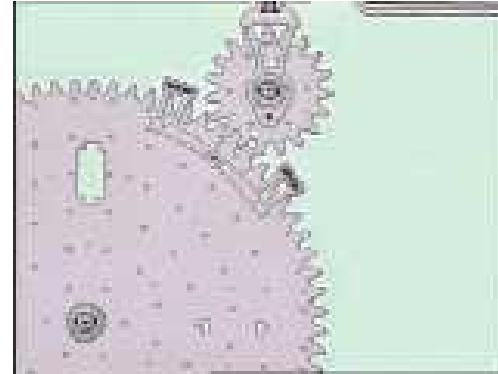
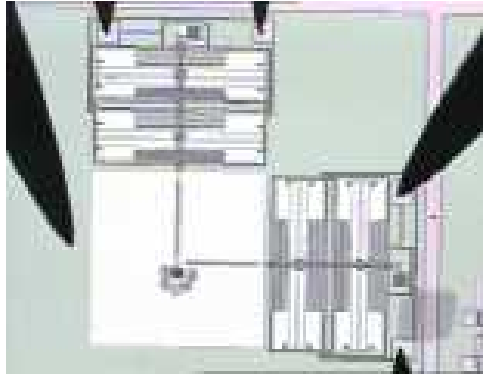
Vibration mode shape of
array with 10 picogram (10^{-14}
kg) mass attached.



Sandia's Actuator Examples

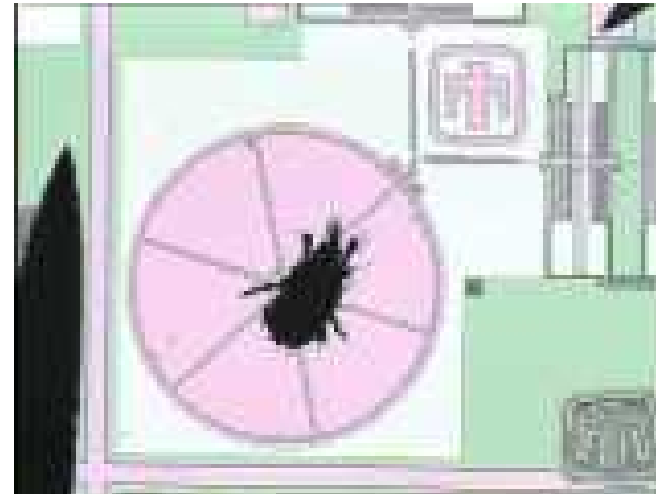
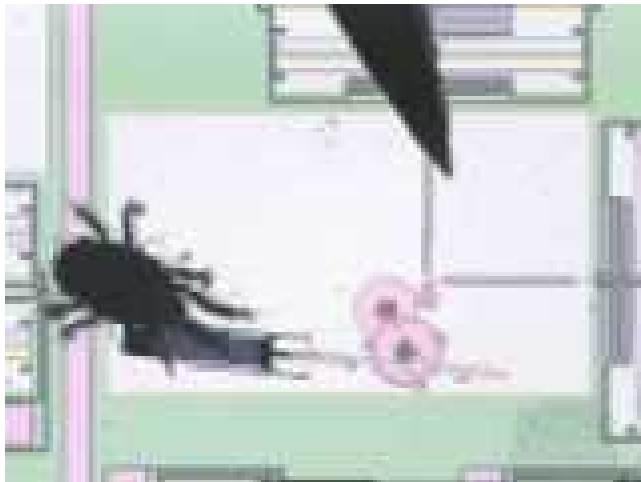
A comb-drive actuator can drive many kinds of mirrors.

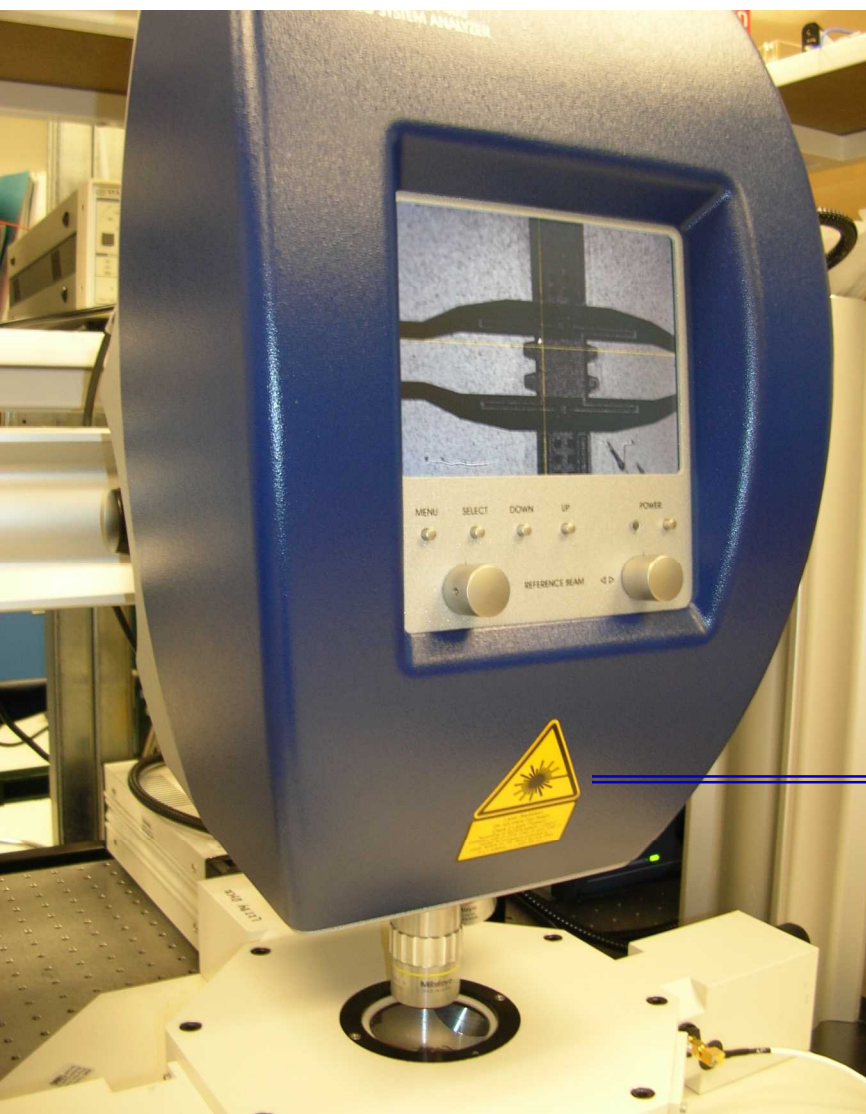
Ejemplos de
motores de
MEMS



The actuation system is robust.

Ejemplos de
motores de
MEMS





Many people from Sandia National Laboratories in Albuquerque, New Mexico, USA contribute to this presentation.

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?Preguntas?

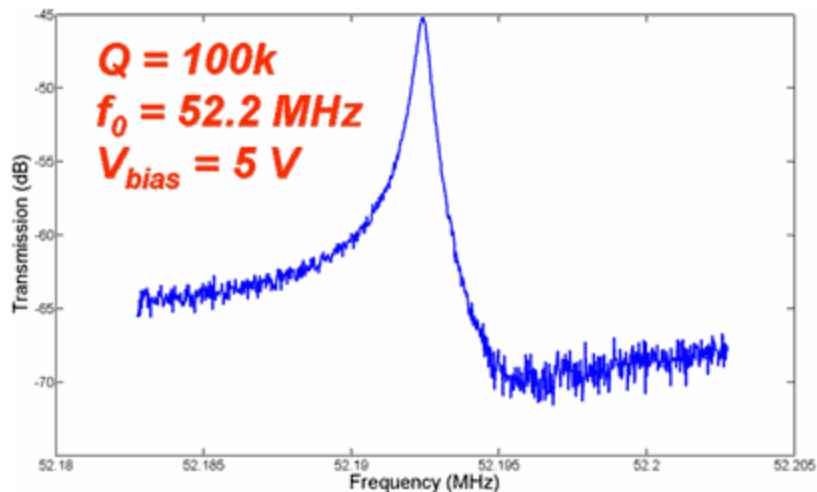
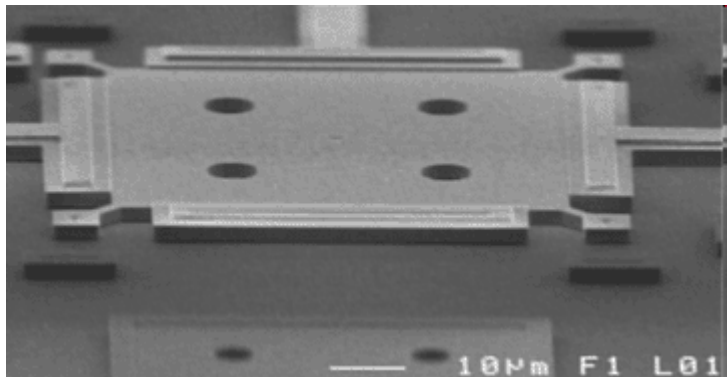
Gracias!

hSumali@Sandia.gov



- Radio Frequency MEMS

Narrow-gap Polysilicon RF MEMS Resonators



A polysilicon MEMS resonator process has been developed at Sandia for the fabrication of high-Q oscillator references and intermediate frequency (IF) filters. This process can achieve electrode-to-resonator gaps less than 100 nm, which is needed to reduce the impedance of capacitively transduced devices. While high frequency resonators can be implemented in this process, it is best suited for fabricating resonators below 200 MHz because the impedance levels are significantly lower at these frequencies. Advantages of these polysilicon resonators when compared to microfabricated piezoelectric resonators include much higher Q ($> 60,000$), low drift, tunability, and low vibration sensitivity. These properties make polysilicon resonators ideal for implementing miniature oscillators and IF filter banks for RF MEMS applications.

SAMPLES™ Program

Price List

Cost Subject to Change without Notice

MEMS Courses

Designing for the SUMMIT V Process using AutoCAD	\$1000
Includes course CD	

MEMS Software Tools

Sandia MEMS Design Tool Suite	\$10000
Includes the following: Sandia Advanced MEMS Design Tools, 2D Process Visualizer, 3D Visualizer, 3D Modeler Generator, Standard Components Library	

Fabrication

SUMMIT V Agile Prototyping, US Institutions (100 unreleased modules)	\$11,200/design Module
SUMMIT V Agile Prototyping, Non-US Institutions (100 unreleased modules)	\$17,200/design Module
(shared reticule) Partnering available for qualifying organizations. Please contact memsinfo@sandia.gov for information.	
HF Release & Dry - One Batch (approximately 50 modules)	\$1500
Release service includes supercritical drying (CO2)	
VSAMS Coating	\$400/batch (approx. 50 die)
Custom post processing	\$Case by Case

MEMS Packaging

Parts designed with standard pad frames, Aluminum Metal and packaged in 24-pin or 48-pin DIP packages	
Double or Single SUMMIT Module	\$3000
Packaging Set up Fee (includes cost of 30 packaged parts)	

MEMS Testing

Testing	\$2000/day
Super µDriver and Amplifier Design CD	License through TEGAM
Reliability	\$1500/day

Additional Service/Technical Support

Custom Design/Design Consulting	\$Case by Case
Limited Production	\$Case by Case
Custom Development	\$Case by Case

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