Dynamic Measurement of PRISM Devices
Arvind Raman and Ryan Tung
Purdue University

Annual Review
October 31 and November 1, 2011
Overview

- Review of Y1 and Y2 measurements of gas damping
- Transient Pull-in Pull-out dynamics of MEMS switches
- Parameter Calibration
Gas Damping Experiments

PRISM Device

Polytec laser Doppler Vibrometer
Suss PLV-50 Vacuum Probe Station
Frequency
Bandwidth 0-1.5 MHz
Resolution 2.5 $\mu$m/s/Hz
Pressure controllable 760 Torr to 62.5 MicroTorr

$l = 400 \, \mu m$
$t_{struc} = 3 - 4 \, \mu m$
gap = 3 - 4 \, \mu m
$b = 120 \, \mu m$

Calibrated data ($x_1 (m), t_1 (s)), (x_2, t_2), ....$

Hilbert transform
$x(t) \rightarrow A(t), \phi(t)$

Fitting to SDOF model
$A(t) \rightarrow \omega_n, \zeta$

Separating gas damping from intrinsic
$\zeta_{gas} = \zeta - \zeta_{int\,rinsic}$

• 14 Devices
• 16 pressures from 1mT-500T
• 5 replicates of data
• Struc. Damping calc. from <=300mT
Uncertainty quantification of gas damping

14 devices, multiple wafers, five replicates

Plots starting from 300mTorr to 500T, Kn based on 3um gap height

- Most variation is wafer to wafer
Overview

- Review of Y1 and Y2 measurements of gas damping
- Transient Pull-in Pull-out dynamics of MEMS switches
- Parameter Calibration
Transient Pull-in Dynamics - an Example

Wavelet Transformation shows excitation of higher eigenmodes at contact events.

NON-PRISM Device Collaboration with Prof. Peroulis and Adam Fruehling

Response to Square Wave Input

Beam Displacement vs. Time
Transient Switch Dynamics - Doubly Clamped PRISM Device

- PRISM Doubly Clamped Device
- Square Wave Input,
- Time Ensemble Measurement
Transient Switch Dynamics - Cantilever PRISM Device

- PRISM Cantilever Device
- Square Wave Input,
- Time Ensemble Measurement
Pull-in Pull-out Measurements

- Triangle Waveform bias was applied to the beam, and the resulting velocity vs. time was measured, bias travels through positive and negative voltage to mitigate dielectric charging.
- Details discussed in Prof. Peroulis’ talk.

![Graph showing Pull-in and Pull-out measurements with normalized voltage and velocity over time.](Image)
Transient Switch Dynamics - Possible Alternate Validation Metrics

Important Metrics:
- Maximum Pull-in Velocity
- Time to Maximum Velocity

Die 9 (200 um long Cantilevered Devices) 7 devices 20 replicates

Response to Ramp Input
Max. Pull-in Velocity
Time to Max. Velocity

PRISM
NASA Center for Prediction of Reliability, Integrity and Survivability of Microsystems
Overview

- Review of Y1 and Y2 measurements of gas damping
- Transient Pull-in Pull-out dynamics of MEMS switches
- Parameter Calibration
Parameter Calibration- Residual Stress

• Pull-in deflection vs voltage being used along with coarse grained model to estimate residual stress in PRISM doubly clamped beams

• We are investigating two alternate methods to directly calibrate residual stress
  (a) Use purely structural vibration modes, instead of measured pull-in voltage
  (b) Use AFM to measure flexural and torsional stiffness (see poster)

• Advantages- Less uncertainties do to gap variation, electrostatics, and noise near instabilities
Residual Stress Calibration using Multimode frequencies

**Knowns** Young’s Modulus \([E]\), beam thickness \([t]\)

**Unknowns** Residual Stress \((N)\), Boundary Conditions \((k_c)\), Initial Curvature \((\gamma)\)

From model

\[
\omega_{B2} = f_{cn}(k_s, N)
\]

\[
\omega_{B4} = f_{cn}(k_s, N)
\]

Experimentally measured modal frequencies of 26 doubly clamped PRISM devices
Parameter Calibration

Bayesian Network

Experimental Data - Measured Frequencies

Theoretical Frequency Model

Input Distributions

- \( E \) Young's Modulus
- \( N \) Residual Stress
- \( E_{\text{model}} \)
- Boundary Condition
- Curvature
- \( B1, B2, B4 \)

Error in Data, assume Zero Mean, Normal Distribution

Std. of Noise in Data (Calibrated)

Non Destructive Test to Calibrate Material Properties

Error in Data, assume Zero Mean, Normal Distribution
Thank You
Damping transitions in freely vibrating cantilevers

Free Molecular Regime

Transition + Slip Flow Regime

Continuum Regime

$K_n$ based on width of the cantilever

Repeatability analysis done only for Cant. C with 15 readings at every pressure.

$\frac{\text{Std. Dev.}}{\text{Mean}} < 2.5\%$

Quantifies the noise in the measurement and extraction

Horizontal bars signify the uncertainty in pressure readings

Mode dependence of squeeze film damping

Mode 1 (12174 Hz)  
Mode 2 (76425 Hz)  
Mode 3 (214000 Hz)

\[ \text{Kn} = \frac{\lambda}{h_o} \]

\[ \text{Re} = \frac{\omega \rho h_o^2}{\mu} \]

Non-monotonic pressure dependence

Freeely Vibrating Cantilever

Cantilever on Squeeze Film

Doubly Clamped Beam on Squeeze Film

PRISM Cantilever Biasing
Pull-in Pull-out Measurements

Bias Corrected Displacement

- Time [ms]
- Normalized Voltage
- Normalized Displacement

PRISM
NSF Center for Prediction of Reliability, Integrity and Survivability of Microsystems