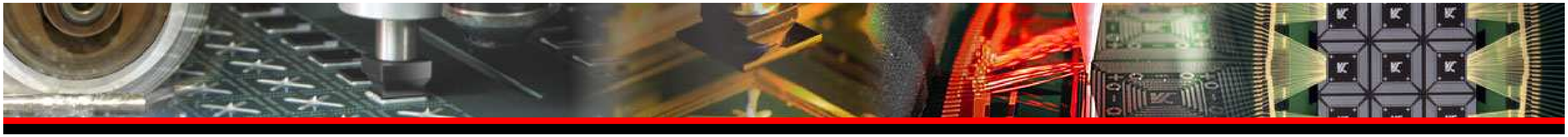
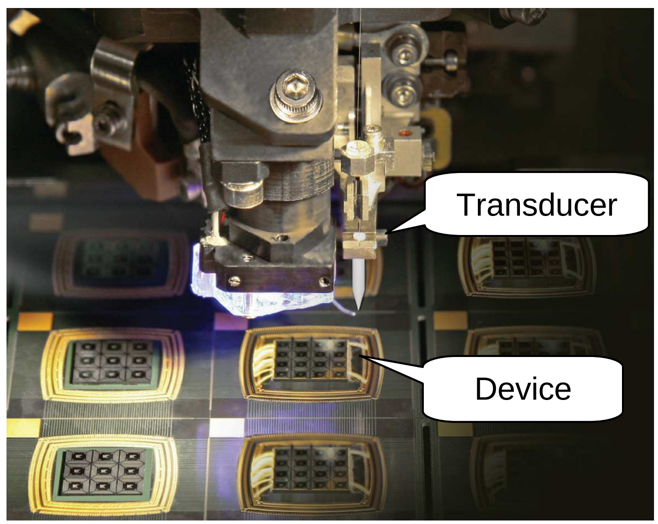


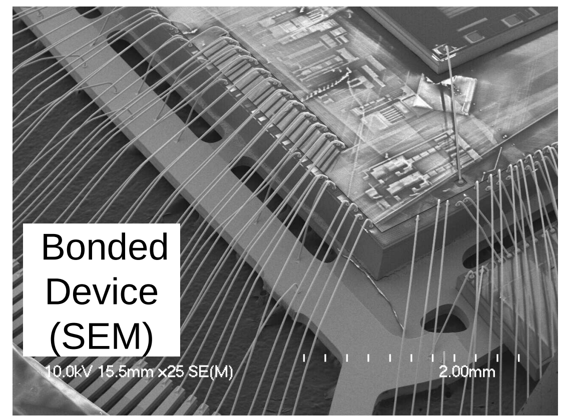
Optimizing Piezoelectric Ceramic Thickness in Ultrasonic Transducers

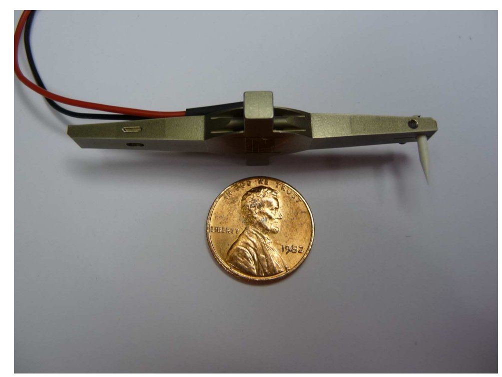
Dominick A. DeAngelis
And
Gary W. Schulze

Kulicke & Soffa's Flagship
Semiconductor
Wire Bonding Machine



Wire Bonding in Action with Fine
Gold Wire (20 Wires/Sec)

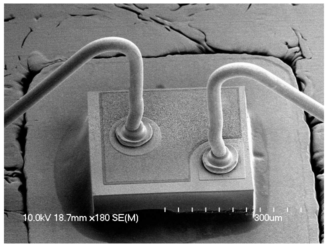
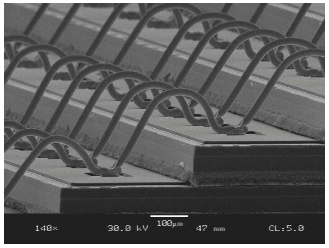
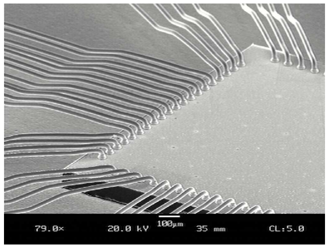
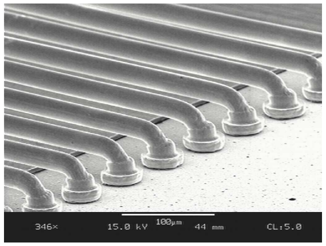
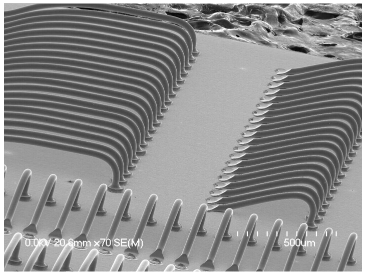
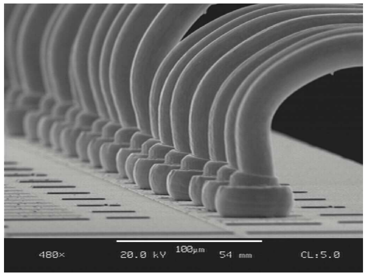
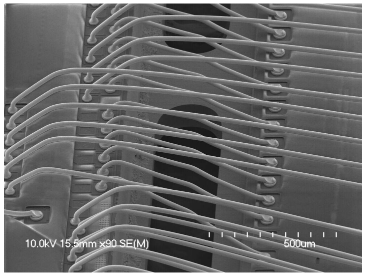
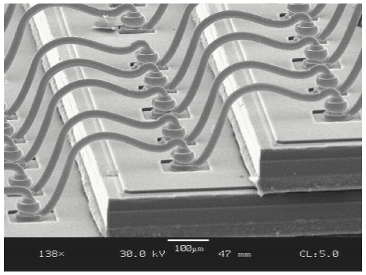
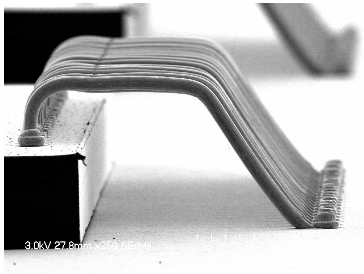




Ultrasonic Transducer Used For
Wire Bonding Machine

OUTLINE

- Motivation for the Work
- Specific Transducer Application
- Research Summary
- Experimental Methods & Metrics
- Equivalent Circuits
- Admittance (Y) Loop
- Finite Element Modeling
- Experimental Results
- Conclusions
- References
- Questions

MOTIVATION FOR THE WORK

- The Thickness of the Individual Piezo Ceramics Should be One of the Most Fundamental Decisions Made by Designers of Ultrasonic Transducers

- The Overall Piezo Stack Length is Normally Determined by “Rule of Thumb” Guidelines Based on the Resonant Wavelength (e.g., ¼ Wave)

- Quite Often Thickness/Number of Individual Piezo Ceramics is Determined by the Drive Electronics (e.g., Maximum Voltage), Rather Than by Fundamental Transducer Design Principles

- Transducer Based Methods and Metrics are Needed to Quantify Performance Based on the Thickness/Number of the Piezo Ceramics for a Given Overall Stack Length

MOTIVATION CON'T

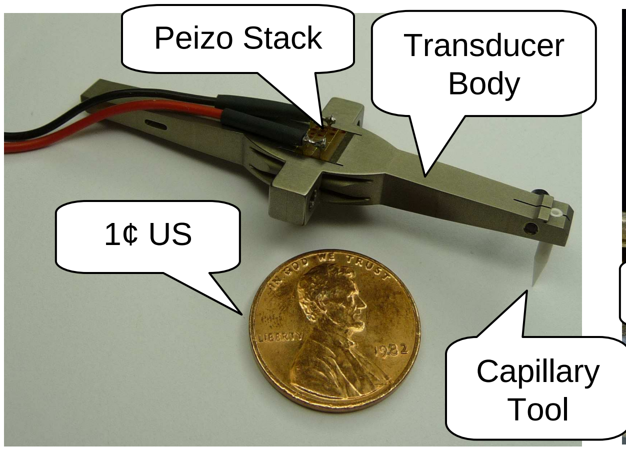
Why is Optimizing Piezo Ceramic Thickness So Important?

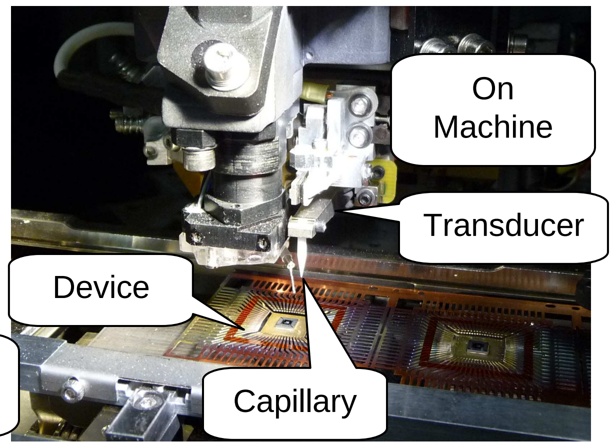
- Thinner Ceramics Result in:
  - Higher/More Uniform Electric Field for a Given Voltage
  - Lower Impedance—Higher Current for Given Voltage
  - Increased Number for a Given Stack Length—Increased MFG Costs
  - More Joint Interfaces—Increased Mechanical Losses
  - Four Fold Capacitance Increase with Thickness—Drive Issues (e.g., Halving the Thickness Doubles Capacitance/Number)

- Thicker Ceramics Result in:
  - Lower/Less Uniform Electric Field for a Given Voltage
  - Higher Impedance with More Internal Heating
  - Reduced Complexity—Increased Reliability, Lowered MFG Costs
  - Less Joint Interfaces—Reduced Tolerance Stackup
  - Four Fold Capacitance Reduction with Thickness—Drive Benefits (e.g., Doubling Thickness Halves Capacitance/Number)

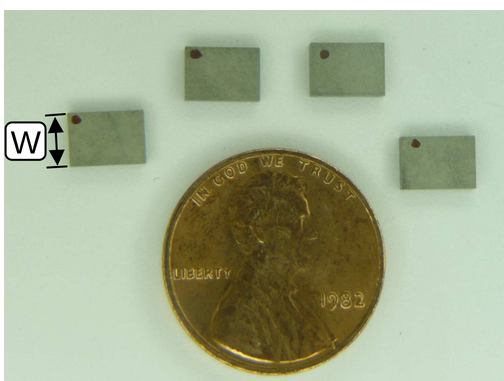
SPECIFIC TRANSDUCER APPLICATION

- K&S is the Leading MFG of Semiconductor Wire Bonding Equipment
- Transducer Delivers Energy to a Capillary Tool for Welding Tiny Wires
- Patented Single Piece “Unibody” Design Ideal for Research Study
- Portability Across 100’s of Machines Required for Same Customer Device

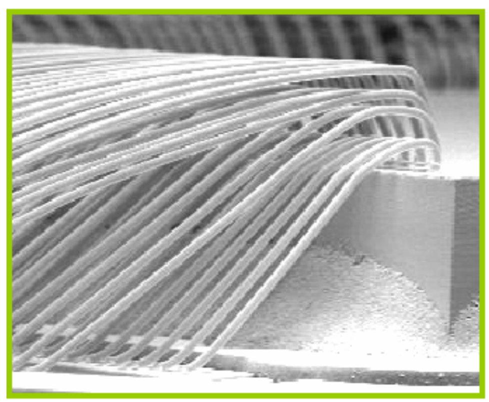




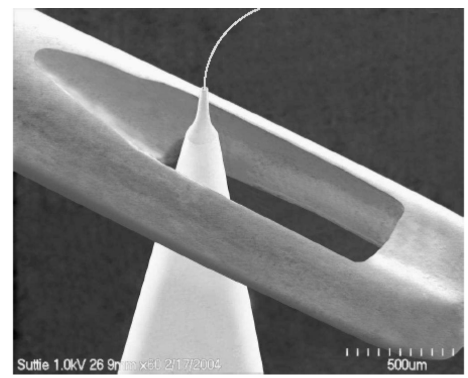
Transducer Specs
500 mA Max Current
120 kHz Operating Mode
80 Ohm Max Impedance
Operation 40 Bonds/Sec
Bond Duration ~10 mSec
PZT8 Ceramics (4X)



PZT8 Piezoelectric Ceramics



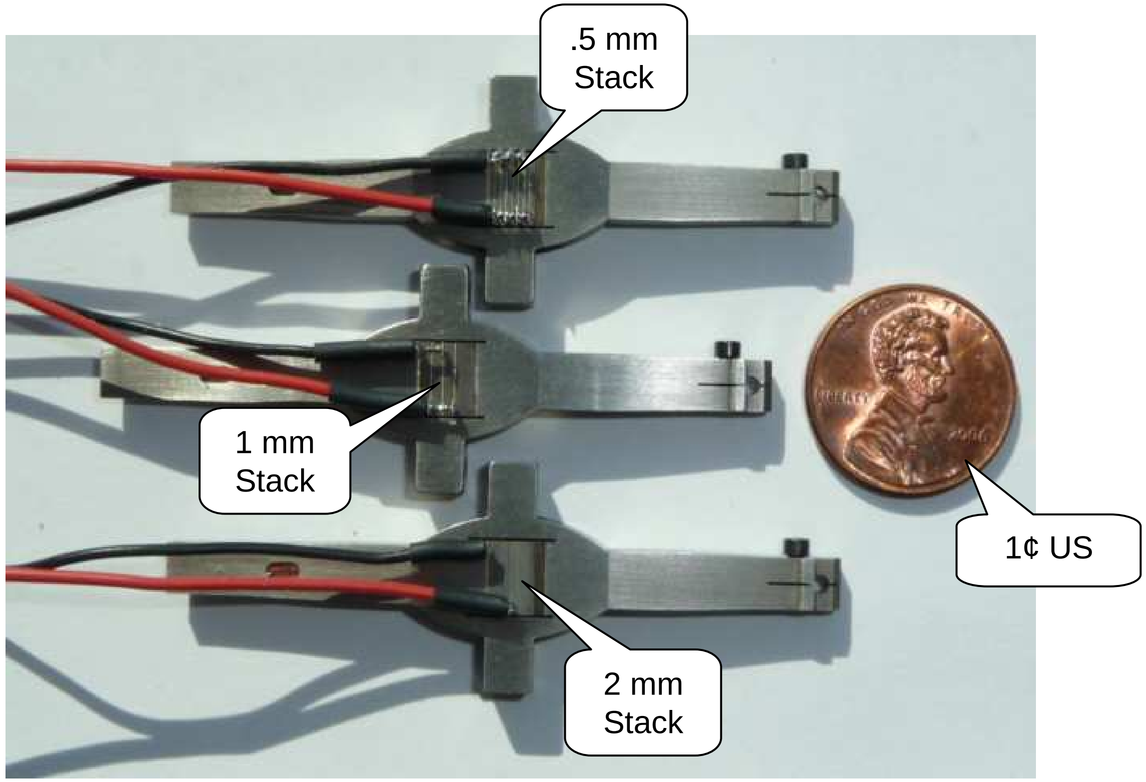
Actual Wire Bonds From of a Multi-Tier Package



Typical Capillary Tool with Wire Compared to Sewing Needle

RESEARCH SUMMARY

- Three Transducers Built with .5 mm, 1 mm and 2 mm Thick Piezo Ceramics
- Transducers Bodies/Piezo Ceramics from Same Production/Powder Lot
- Overall Transducer Piezo Stack Length Identical for All (# of Shims Varies)
- Transducers Subjected to Stabilizing Heat-Treatment After Build

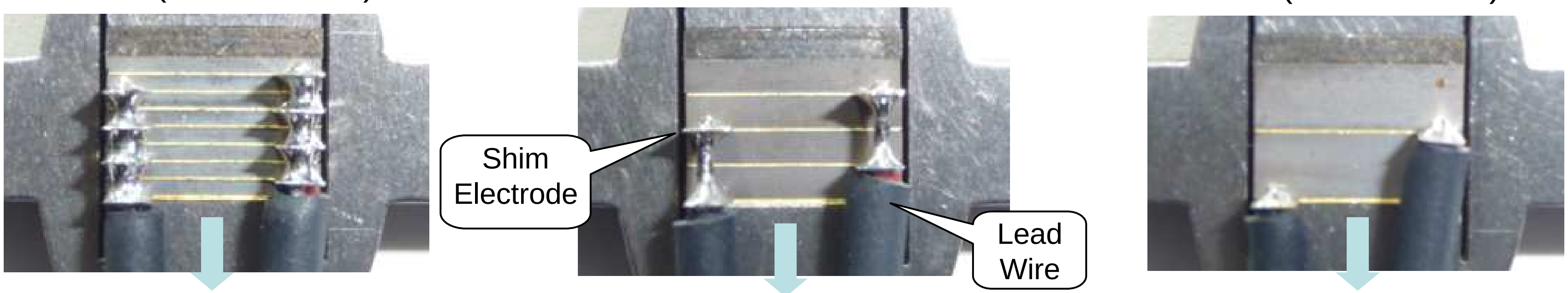


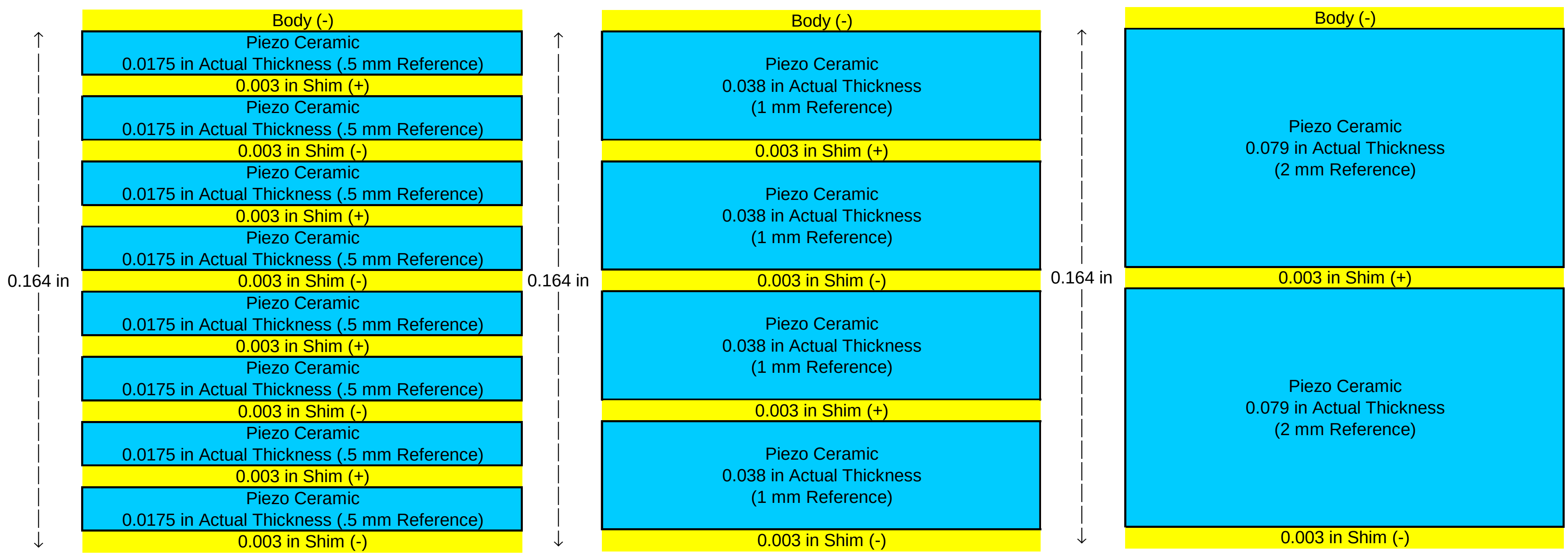
The Three Transducers Built for this Research Study

RESEARCH SUMMARY CON'T

- Detailed Configuration of .5 mm, 1 mm and 2 mm Piezo Stacks

.5 mm (8X Ceramics) | 1 mm (4X Ceramics, Baseline) | 2 mm (2X Ceramics)





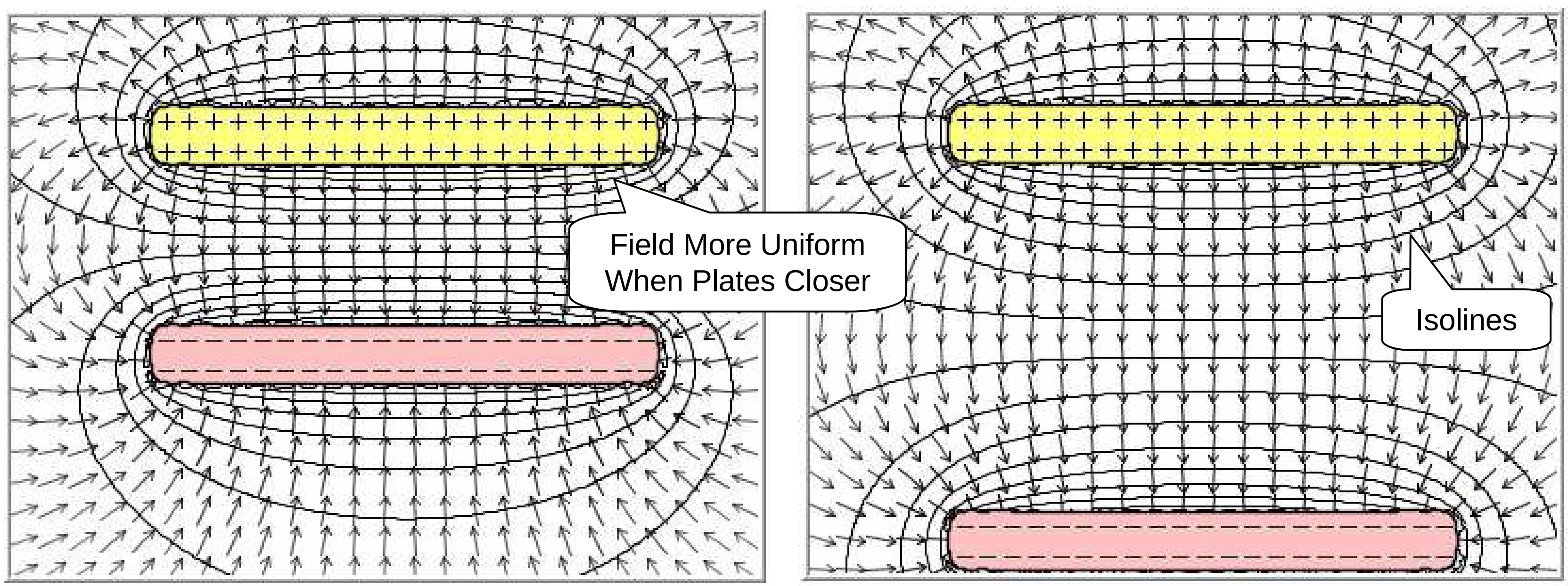
RESEARCH SUMMARY CON'T

❖ Vendor Provided Data of PZT8 Ceramics for Each Thickness Prototype

Averaged Vendor Data from 25 Sample Inspection of Each Thickness Size
(All Thickness Sizes Made from Same PZT8 Powder Lot 505, Bode in Width "W" Mode)

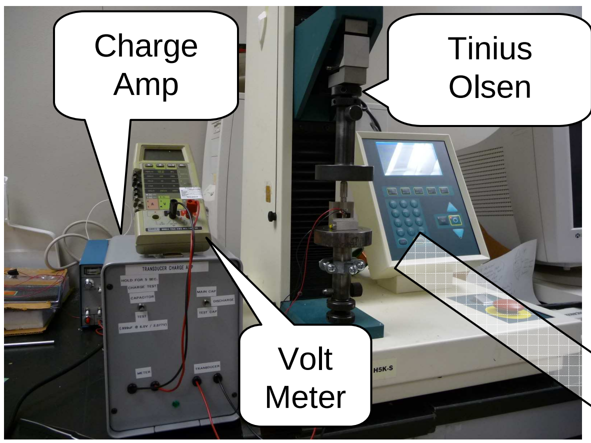
Ref Thk (mm)	*Actual Thk* (in)	*Powder Lot*	*Pole Date*	*Test Date*	f_a (Hz)	f_r (Hz)	Z_r (Ω)	$\frac{f_a - f_r}{f_r}$	*C* (pF)	k_{31}	K^T_{33}	*DF*	d_{33}	Q_m
0.5	**0.0175**	505	05-Jan-10	10-Feb-10	451798	409643	11	0.103	653	0.469	-	0.0016	-	328
1.0	**0.0380**	505	28-Nov-09	09-Feb-10	453972	411366	-	0.104	285	0.470	1097	0.0020	252	-
2.0	**0.0790**	505	05-Jan-10	10-Feb-10	445145	396640	22	0.122	136	0.505	-	0.0027	-	691

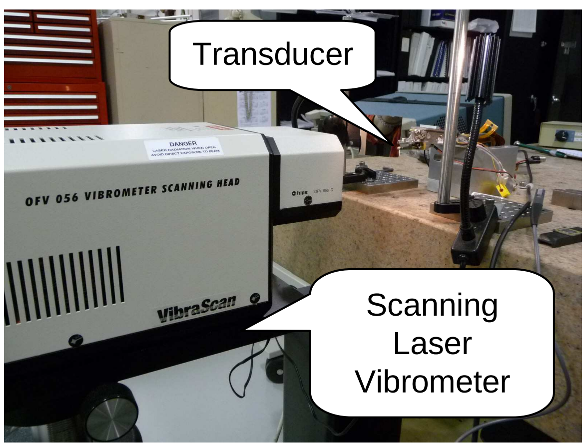
❖ Comparison of Parallel Plate Electric Field Uniformity Based on Distance

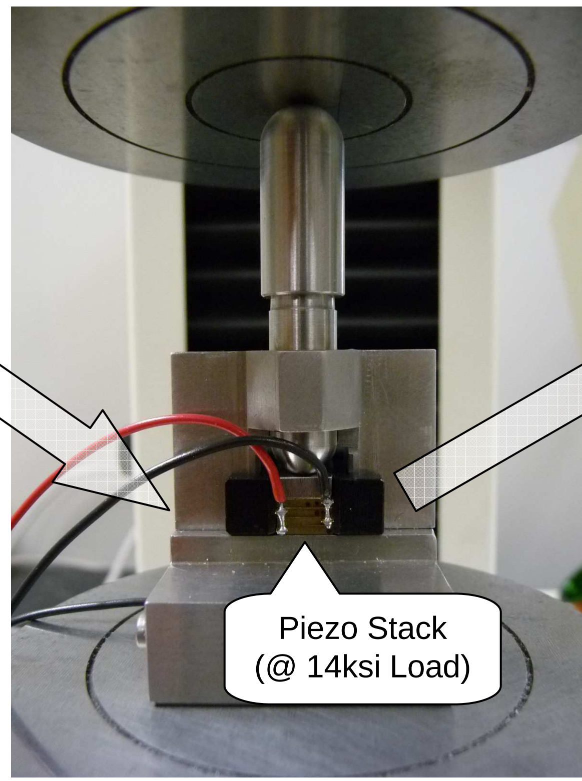


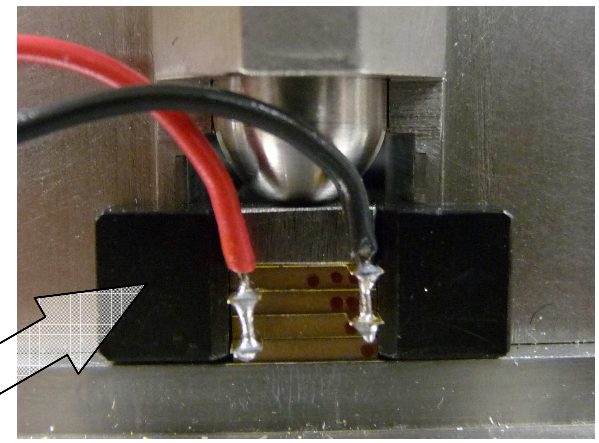
EXPERIMENTAL METHODS & METRICS

- Bode Plots, Capacitance, DF of Individual Piezo Ceramics Before Build
- Calibrate Stack Voltage vs. Force Prior to Assembly to Match Preload
- Bode Plots, Capacitance, DF of Transducer After Heat-Treatment
- Laser Vibrometer Gain Measurements After Heat-Treatment

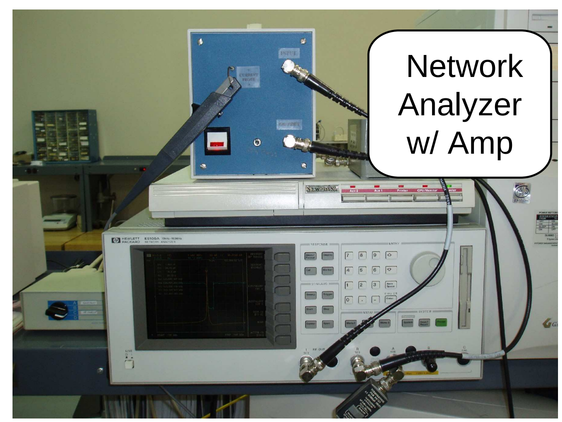






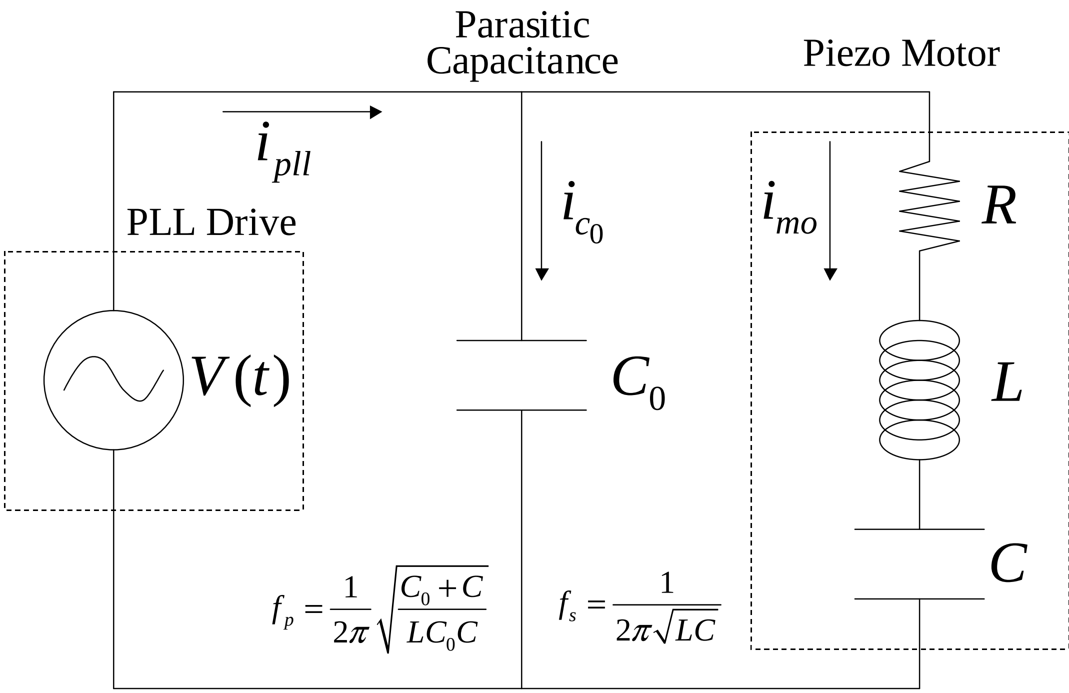


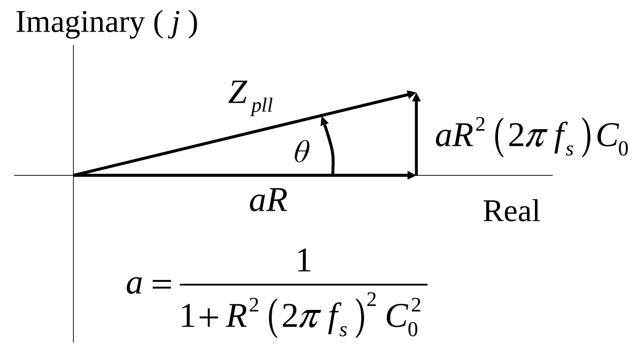
Stack Voltage vs. Force Calibration Fixture (Before Assembly)



EQUIVALENT CIRCUITS

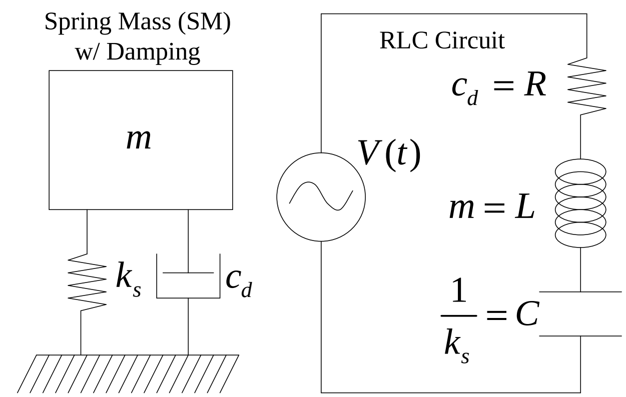
- For f_s Series Resonance Frequency $i_{pll} \approx i_{mo}$ and $i_{pll} >> i_{c0}$
- For f_p Parallel Resonance Frequency $i_{c0} \approx -i_{mo}$ and $i_{pll} << i_{mo}$
- Spacing of f_p - f_s Proportional to Electro-Mechanical Coupling Factor k





Phase Compensation θ for Phase Lock Loop (PLL) Drive to Achieve Series Resonance f_s

$f_p - f_s$ Similar to Antiresonance/Resonance Delta $f_a - f_r$ at PLL Drive for Small C_0



Analog Mechanical Spring-Mass System

ADMITTANCE (Y) LOOP

Imaginary Axis

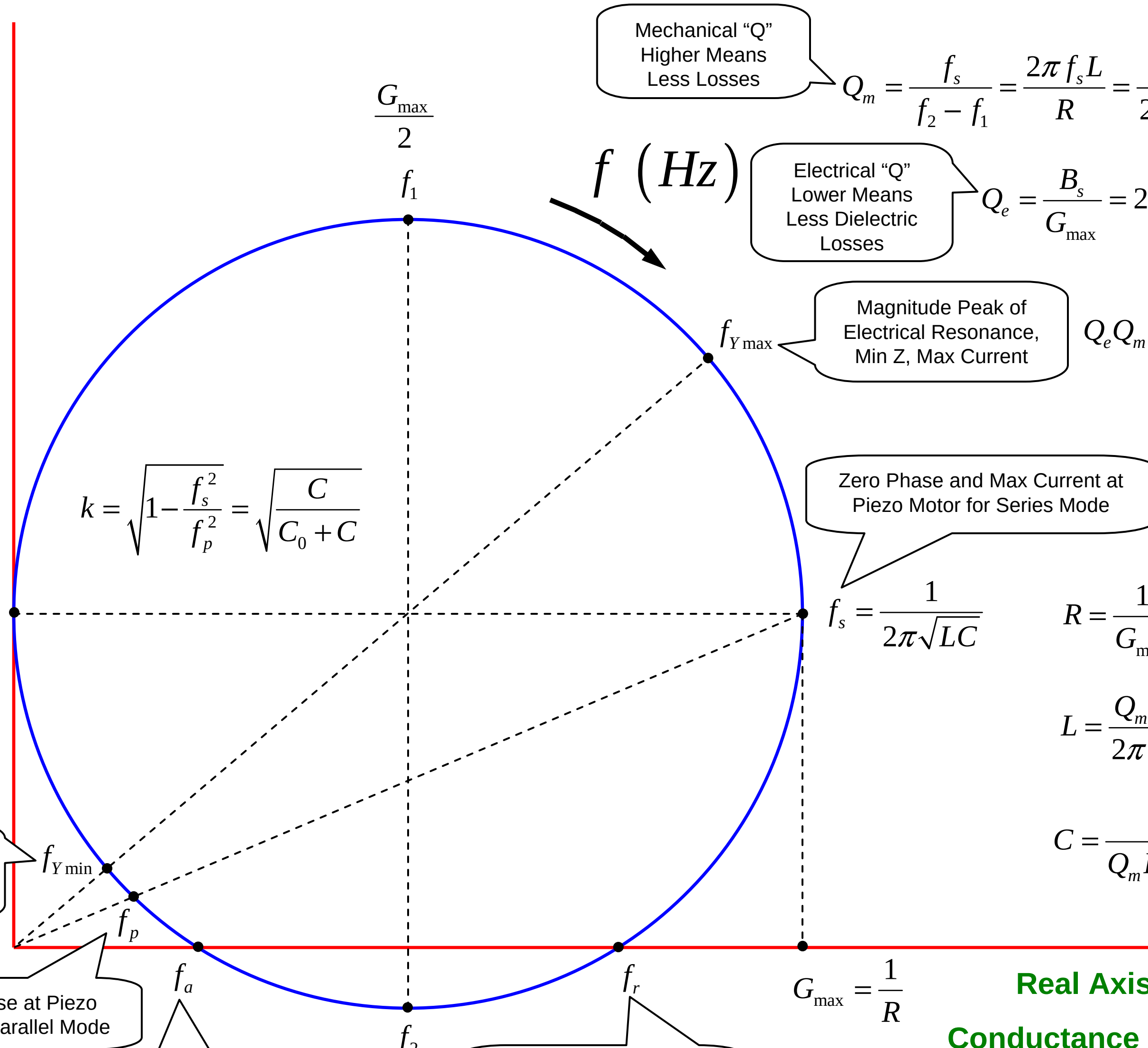
Susceptance *B* (S)

$$Y = G + jB = \frac{1}{Z}$$

Admittance — Conductance — Susceptance

$$Z = R + jX = \frac{V}{I} = \frac{1}{Y}$$

Impedance — Resistance — Reactance



$$k = \sqrt{1 - \frac{f_s^2}{f_p^2}} = \sqrt{\frac{C}{C_0 + C}}$$

Mechanical "Q" Higher Means Less Losses

$$Q_m = \frac{f_s}{f_2 - f_1} = \frac{2\pi f_s L}{R} = \frac{1}{2\pi f_s CR}$$

Electrical "Q" Lower Means Less Dielectric Losses

$$Q_e = \frac{B_s}{G_{max}} = 2\pi f_s C_0 R$$

Magnitude Peak of Electrical Resonance, Min Z, Max Current ($f_{Y\max}$)

$$Q_e Q_m = \frac{C_0}{C} = \frac{1 - k^2}{k^2}$$

Zero Phase and Max Current at Piezo Motor for Series Mode

$$f_s = \frac{1}{2\pi\sqrt{LC}}$$

$$R = \frac{1}{G_{max}}$$

$$L = \frac{Q_m R}{2\pi f_s}$$

$$C = \frac{1}{Q_m R 2\pi f_s}$$

$$2\pi f_s C_0 = B_s$$

$$C_0 = \frac{f_r^2}{f_a^2 - f_r^2} C \approx \frac{B_s}{2\pi f_s}$$

Magnitude Minimum of Electrical Anti-resonance Max Z, Min Current ($f_{Y\min}$)

$$f_p = \frac{1}{2\pi}\sqrt{\frac{C_0 + C}{LC_0 C}}$$

Zero Phase at Piezo Motor for Parallel Mode (f_p)

Zero Phase, Electrical Anti-resonance (f_a)

Zero Phase, Electrical Resonance (f_r)

$$G_{max} = \frac{1}{R}$$

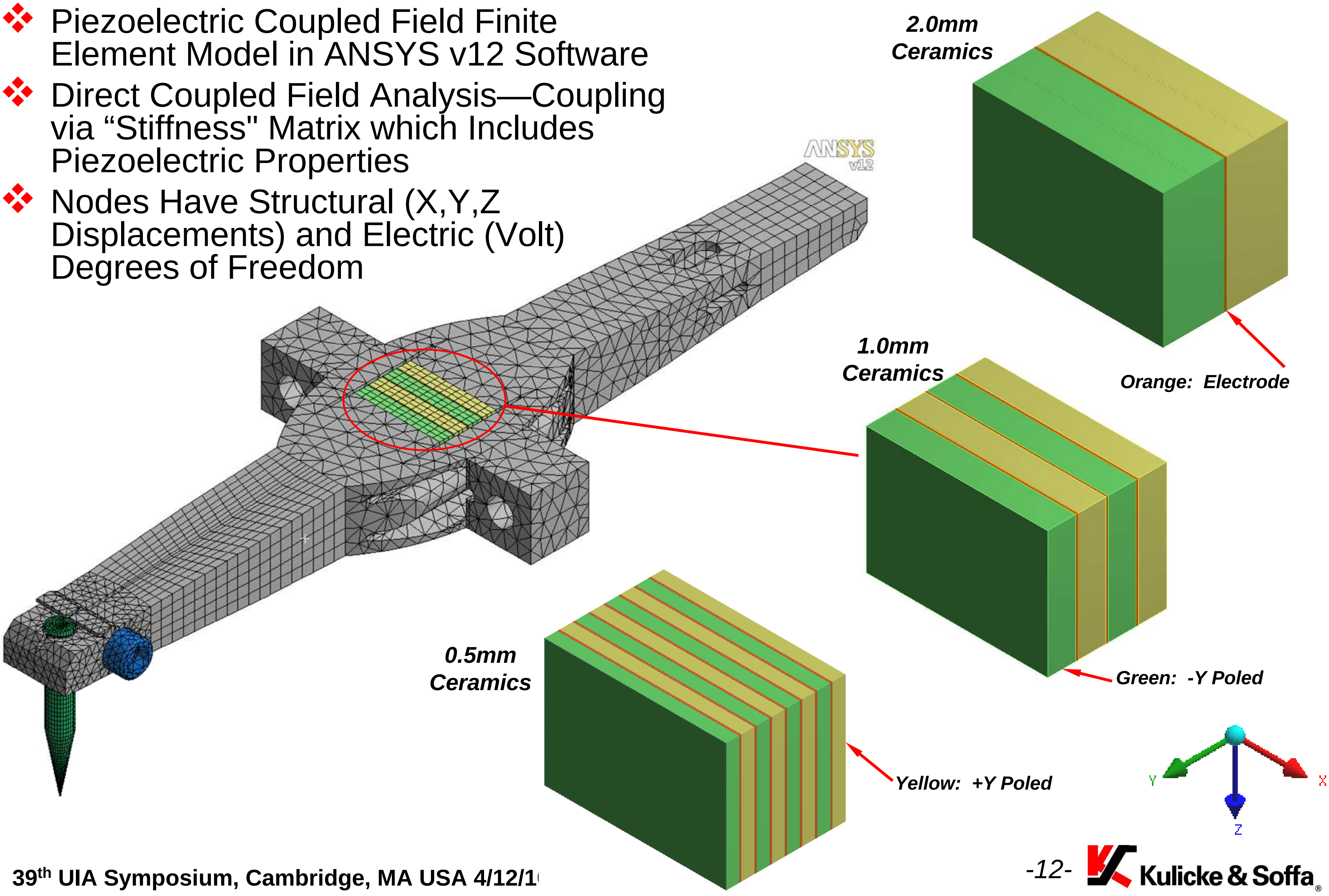
Real Axis

Conductance *G* (S)

$$f_{Y\min} > f_p > f_a > f_2 > f_r > f_s > f_{Y\max} > f_1$$

FINITE ELEMENT MODELING

- Piezoelectric Coupled Field Finite Element Model in ANSYS v12 Software
- Direct Coupled Field Analysis—Coupling via “Stiffness" Matrix which Includes Piezoelectric Properties
- Nodes Have Structural (X,Y,Z Displacements) and Electric (Volt) Degrees of Freedom



FINITE ELEMENT MODELING

- Gain and Bode Results from Finite Element Model
- Constant Damping Ratio of 0.2% Used for All Materials

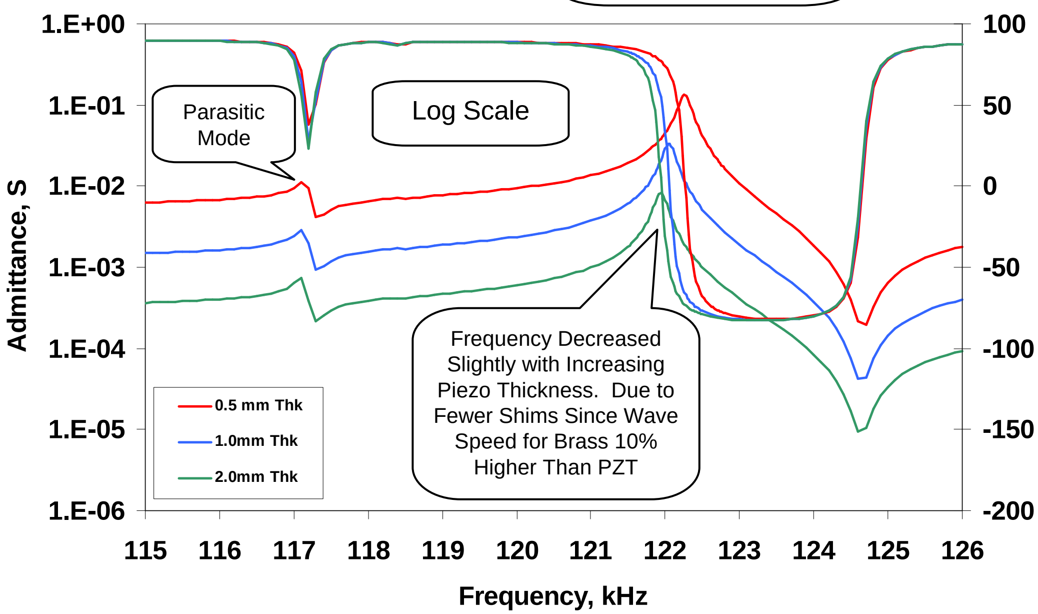
Calculated Transducer Behavior

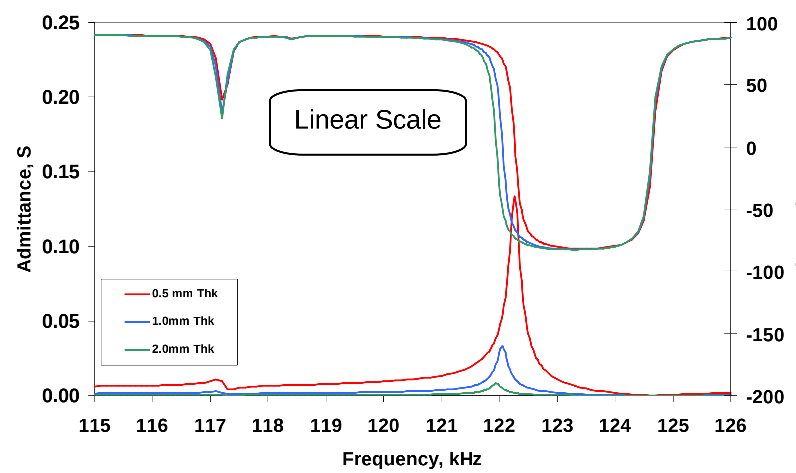
PZT Thickness mm	Frequency kHz	Impedance Ohms	Phase Window kHz	Normalized Gain µm/Volt	Normalized Gain µm/mA
0.5	122.3	7.5	2.38	1.76	0.44
1.0	122.1	30.3	2.58	1.00	1.00
2.0	121.9	121.0	2.67	0.36	1.43
Experimental Correlation	Poor	Good	Fair	Good	Fair

Experiment Showed Opposite Trend

Experiment Showed 1 mm Slightly Wider

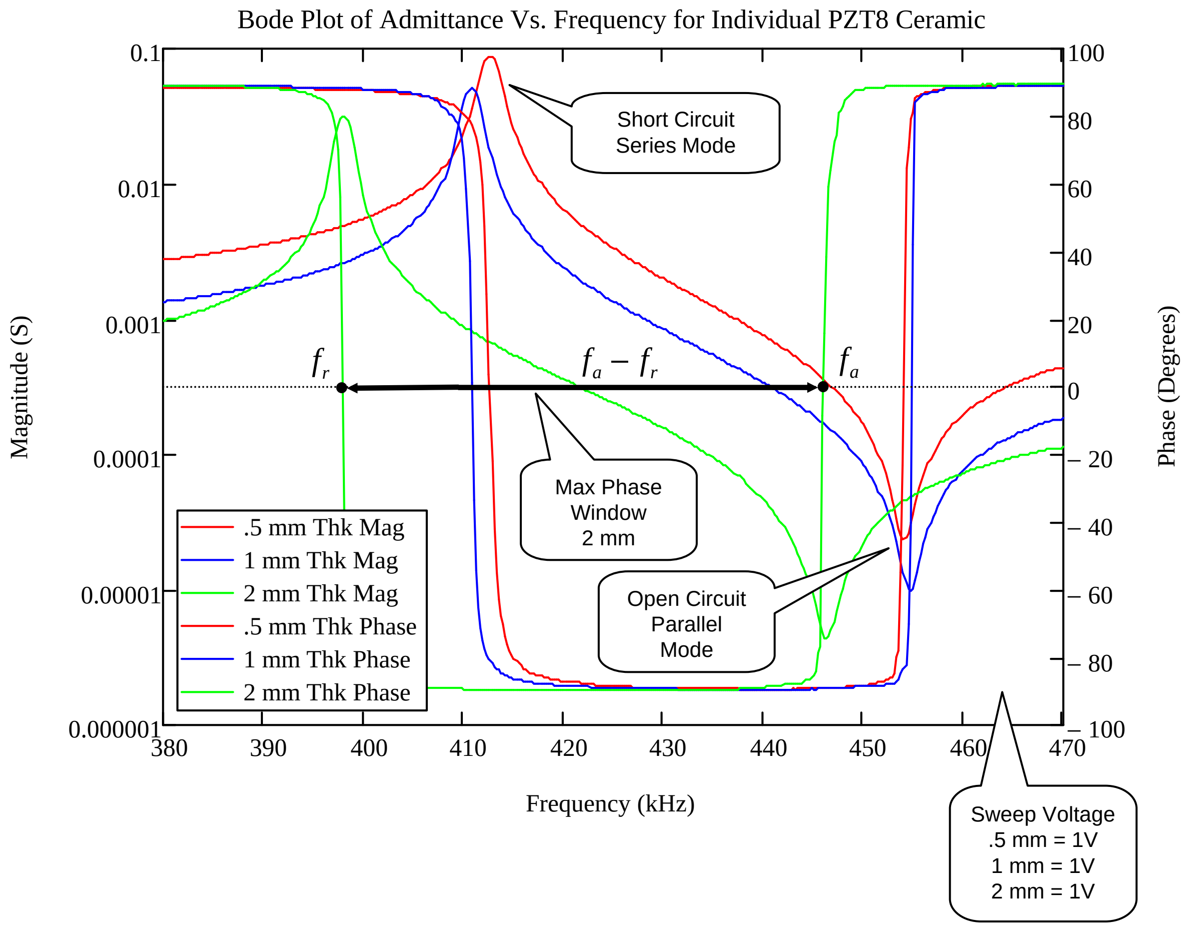
Experiment Showed 2.00 for 2.0 mm? .5 mm & 1 mm Good.

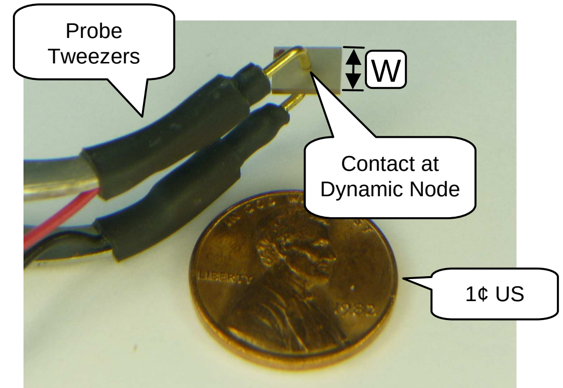




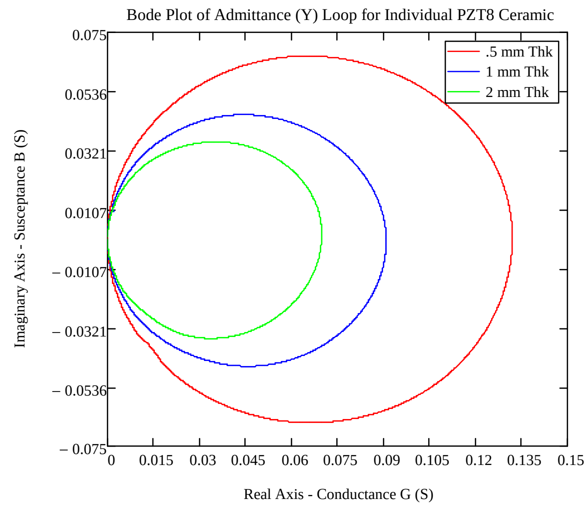
EXPERIMENTAL RESULTS

- Typical Free-Free Bode Plot Results for Individual PZT Ceramics
- Vibrational Mode in Width “W” Dimension of Piezo Ceramic (1V Sweep)
- k_{31} Proportional to Phase Window $f_a - f_r$ (Widest for 2 mm Thk)



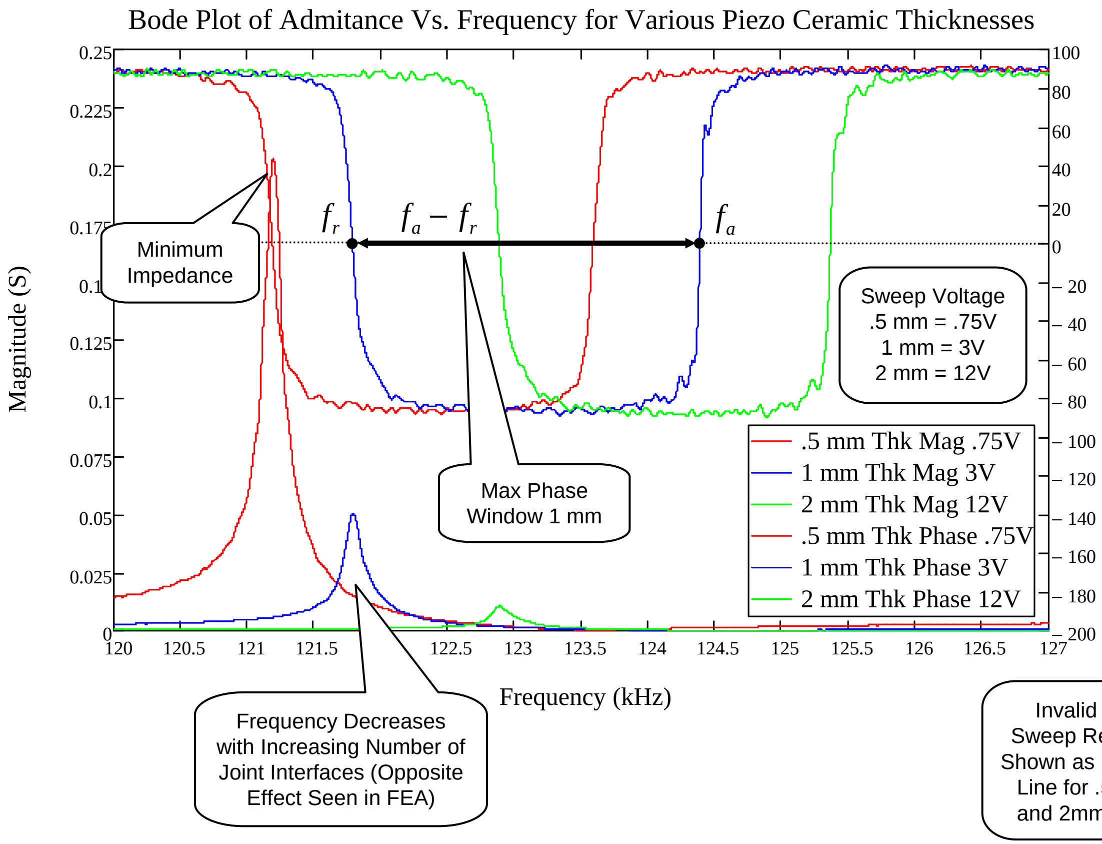


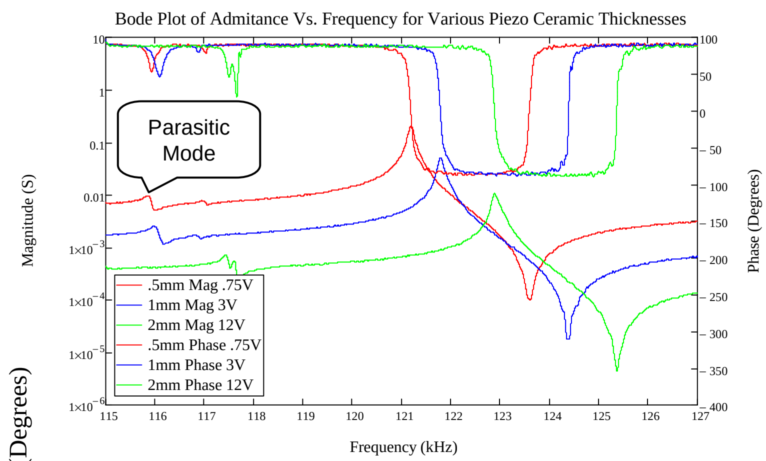
Piezo Ceramic Based Bode Plot Technique

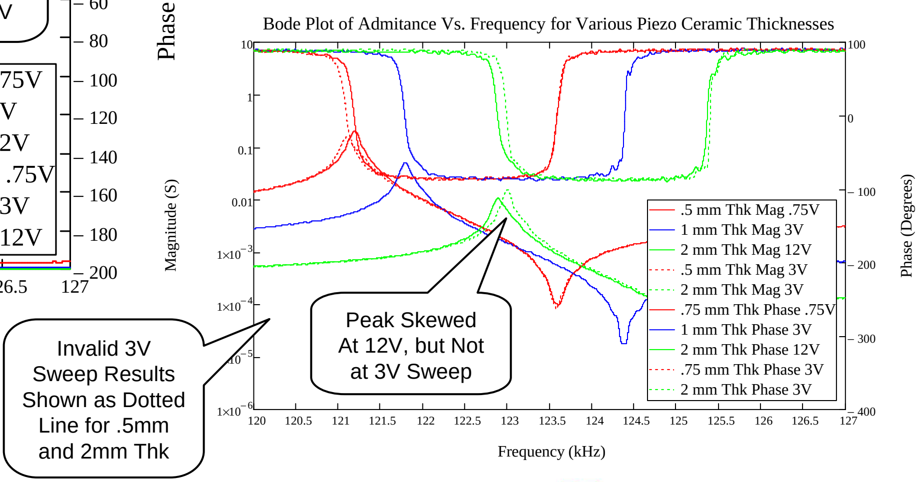


EXPERIMENTAL RESULTS CON'T

- Transducer Bode Plot Results After Stabilizing Heat-Treatment
- Constant Voltage Sweep Normalized to Maximum Current at f_r
- Electro-Mechanical Coupling k Proportional to Phase Window $f_a - f_r$

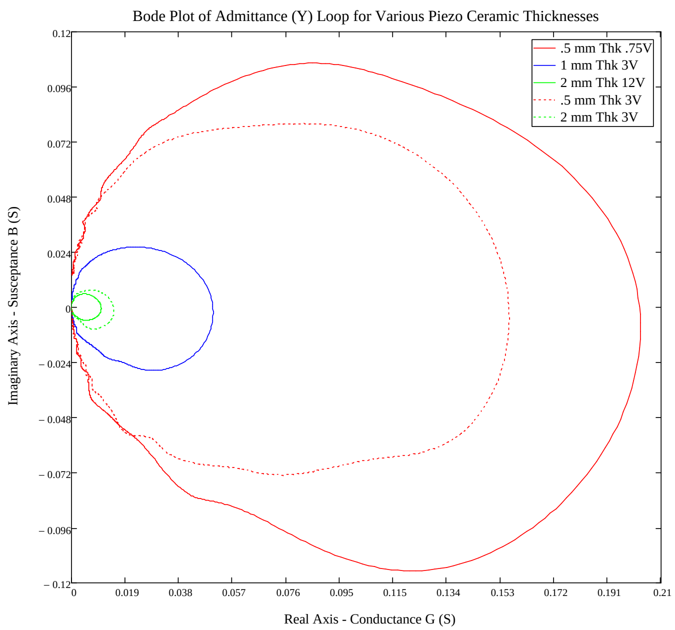


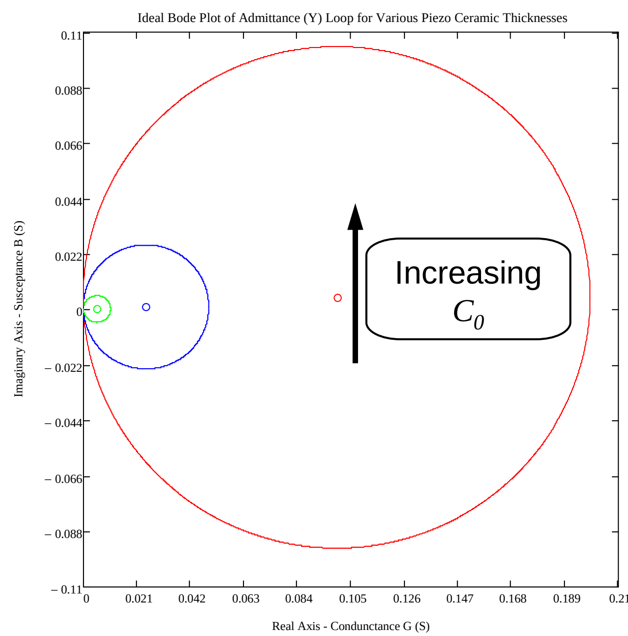




EXPERIMENTAL RESULTS CON'T

- Transducer Admittance Loop Bode and Equivalent Circuit Results
- Find Thickness that Maximizes k and Q_m, but Minimizes Q_e





Analog Mechanical Properties

Ref Thk (mm)	*Stiffnes* (k_s)	*Mass* (m)	*Damping* (c_d)
0.5	3.91E+09	7	5
1.0	1.64E+10	28	20
2.0	7.24E+10	121	94

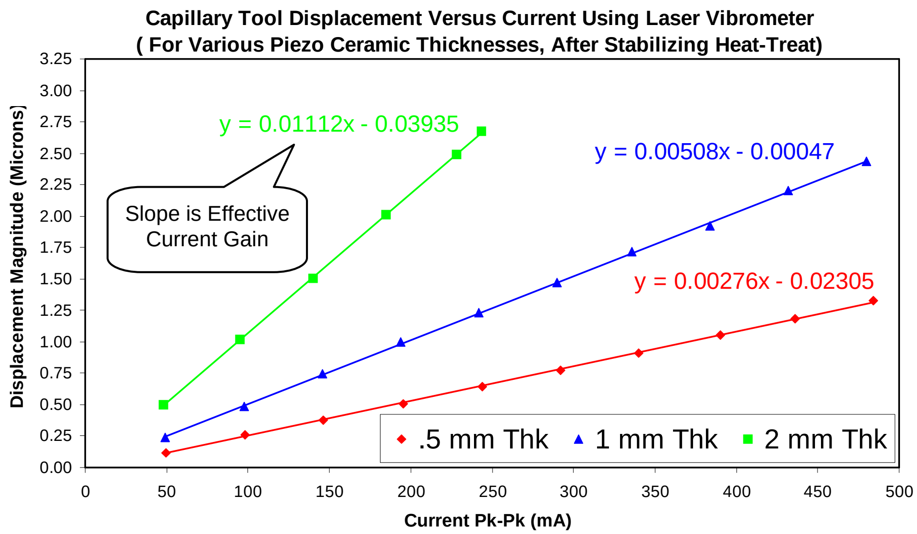
Maximize k
Maximize Q_m
Minimize Q_e

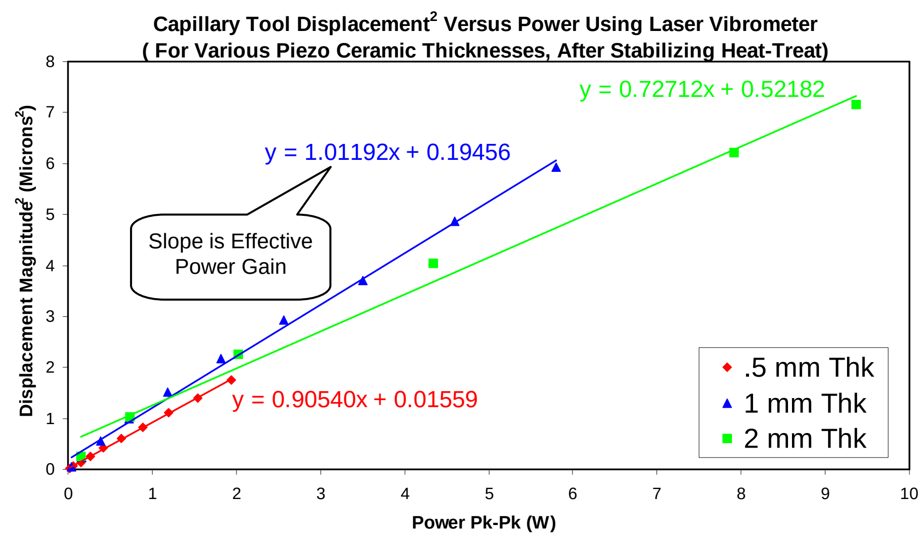
Equivalent Circuit Properties (Invalid 3V Sweep Results Also Shown for .5 mm and 2.0 mm Thk)

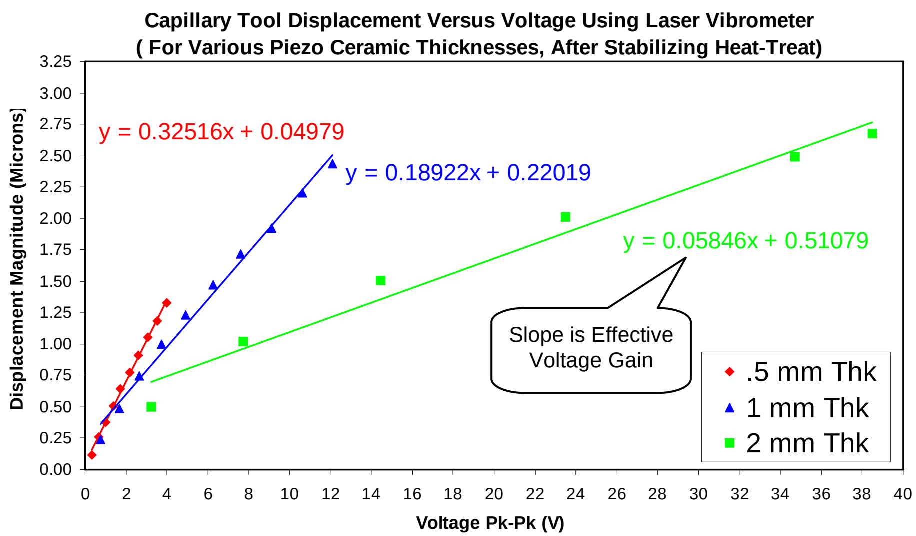
Ref Thk (mm)	*Actual Thk* (in)	*Sweep* (V_{pp})	*Max I* (mA_{pp})	C_0 (pF)	C (pF)	L (mH)	R (Ω)	f_s (kHz)	f_a (kHz)	f_r (kHz)	f_1 (kHz)	f_2 (kHz)	f_p (kHz)	k	Q_m	Q_e
0.5	**0.0175**	0.75	149	6397	256	7	5	121.191	123.585	121.187	121.131	121.250	123.588	0.1960	1022	0.024
1.0	**0.0380**	3.00	148	1416	61	28	20	121.791	124.382	121.786	121.733	121.849	124.391	0.2034	1053	0.022
2.0	**0.0790**	12.00	128	338	14	121	94	122.894	125.366	122.881	122.833	122.956	125.358	0.1973	996	0.025
0.5	**0.0175**	3.00	455	5835	242	7	7	121.113	123.582	121.100	121.040	121.187	123.600	0.1996	824	0.029
2.0	**0.0790**	3.00	43	350	14	121	70	122.992	125.403	122.993	122.946	123.038	125.396	0.1949	1335	0.019

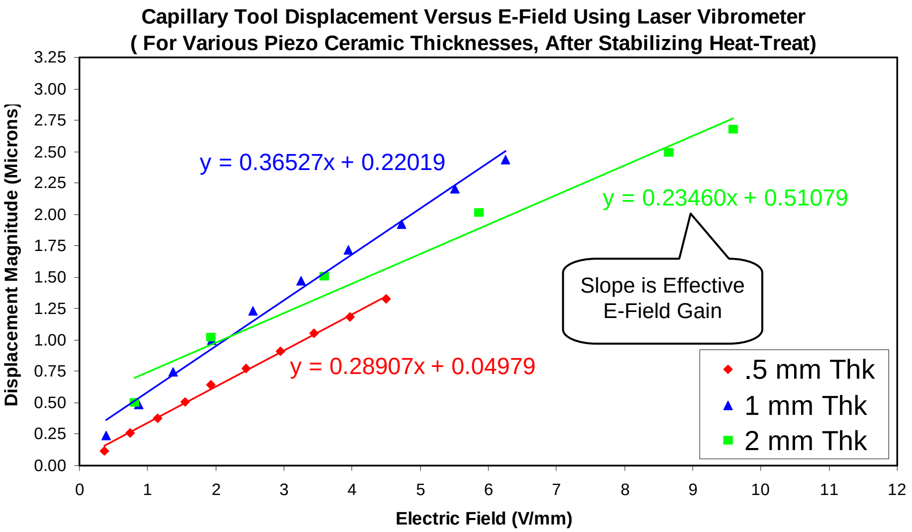
EXPERIMENTAL RESULTS CON'T

- Capillary Tool Displacement Gain Results After Stabilizing Heat-Treat



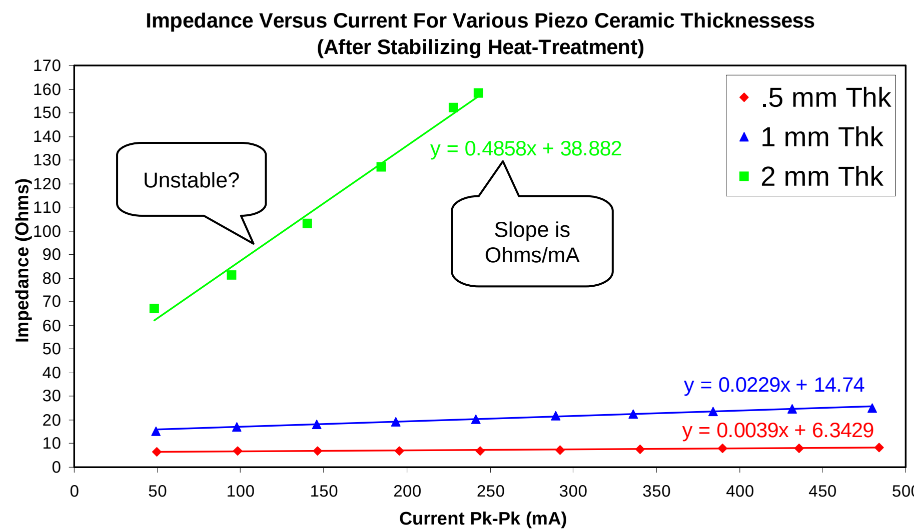


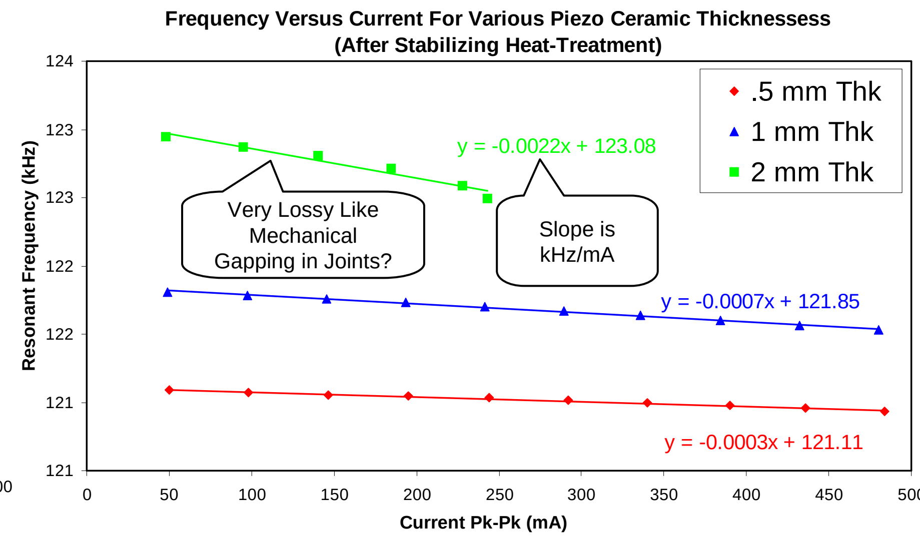


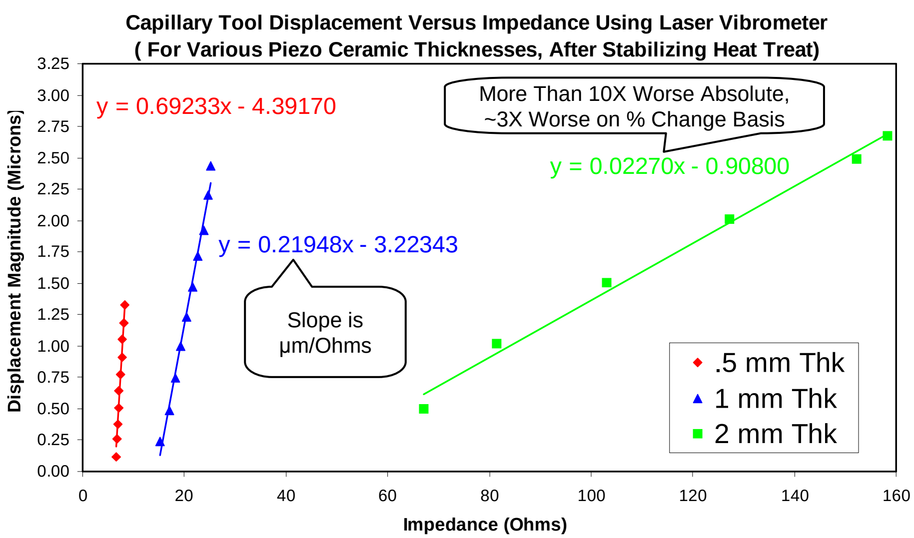


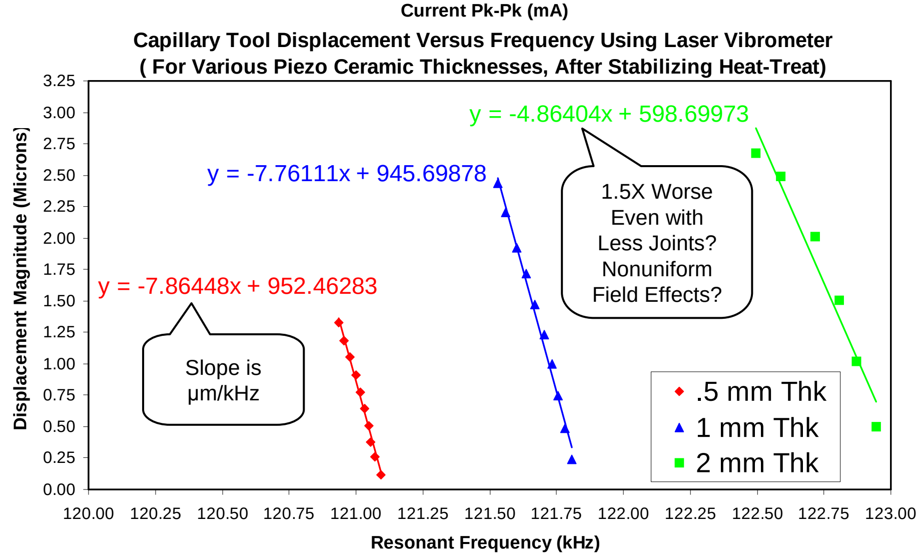
EXPERIMENTAL RESULTS CON'T

- Transducer Impedance/Frequency Sensitivity Results After Stabilizing HT









CONCLUSIONS

Summary of All Experimental Results

Ref Thk (mm)	*Actual Thk* (in)	*LCR (1kHz)*		*Bode Plot*					*Laser Vibrometer*								
		Cap (pF)	*DF*	*R* (Ω)	f_r (Hz)	*k*	Q_m	Q_e	$\frac{\mu m}{mA}$	$\frac{\mu m}{V}$	$\frac{\mu m^2}{W}$	$\frac{\mu m}{V/mm}$	$\frac{\mu m}{\Omega}$	$\frac{\mu m}{kHz}$	*Max Output (µm)* 500mA	40V	20W
0.5	**0.0175**	6519	0.005	5	121187	0.1960	1022	0.024	0.0028	0.325	0.905	0.289	0.692	-7.86	1.40	13.00	4.25
1.0	**0.0380**	1625	0.004	20	121786	0.2034	1053	0.022	0.0051	0.189	1.020	0.365	0.219	-7.76	2.55	7.56	4.52
2.0	**0.0790**	415	0.002	94	122881	0.1973	996	0.025	0.0110	0.058	0.727	0.235	0.023	-4.86	5.50	2.32	3.81

Parameter Sensitivity as Piezo Ceramics Thickness is Increased for a Given Fixed Stack Length

Perfomance Parameters			**Physical Parameters**		
Parameter	***Direction***	***Influence***	***Parameter***	***Direction***	***Influence***
Impedance	↑	Electric Field	Motional Damping	↑	Distance
Resonant Frequency	↑	# Joints	Motional Stiffness	↑	Distance
Electro-Mechanical Coupling	↔	Varies	Shim Material Volume	↓	# Joints
Joint/Interface Losses	↓	Quantity	# Shim Electrodes	↓	Quantity
Nonuniform Electric Field Losses	↑	Distance	Peizo Material Volume	↑	# Joints
Mechanical Quality Factor	↔	Varies	DF Stack	↓	Distance
Electrical Quality Factor	↔	Varies	Capacitance	↓	Distance
Gain µm/mA	↑	Electric Field	Complexity/MFG Cost	↓	Quantity
Gain µm/V	↓	Electric Field	Motional Mass	↑	Distance
Gain $\mu m^2/W$	↔	Varies	DF Ceramics	↑	Distance
Gain µm/(V/mm)	↔	Varies	Electric Field	↓	Distance
Impedance Change µm/Ω	↓	Electric Field	Poling Voltage	↑	Distance
Frequency Change µm/kHz	↓	Electric Field	Piezo Material Cost	↓	Quantity

CONCLUSIONS CON'T

- Optimal Piezo Ceramic Thickness Found to be 1 mm for this Transducer
- Bode Plot Results Were Weak Indicators for 1 mm Decision
- Laser Vibrometer Results Provided More Conclusive Evidence
- Displacement for 1 mm Most Efficient with Respect to Power and Electric Field
- Optimal Design Traded-Off Electric Field Uniformity Vs. # Joint Interfaces
- ANSYS FEA Showed Frequency Shift Effect Not Piezo Related (# Joint Interfaces)
- Design Methodology Presented for Optimizing Piezo Ceramic Thickness

- Summary of 2X Thicker Piezo Ceramics Results Compared to Baseline 1 mm
  - 4X Higher Impedance, But Only 2X Higher Displacement/Current Gain
  - 3X Higher Drive Voltage Required for a Given Displacement w/ 50% Less Current
  - Resonant Frequency Increased Due to Fewer Joints (Increased Stack Stiffness)
  - Larger Variations in Impedance and Resonant Frequency Vs. Displ. (Unstable)

- Summary of Half Thick Piezo Ceramics Results Compared to Baseline 1 mm
  - 75% Less Impedance, But Only 50% Reduction in Current/Displacement Gain
  - Requires Half Drive Voltage for a Given Displacement w/ 200% More Current
  - Only Moderately Worse Based on Performance, But Much Higher Complexity

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QUESTIONS