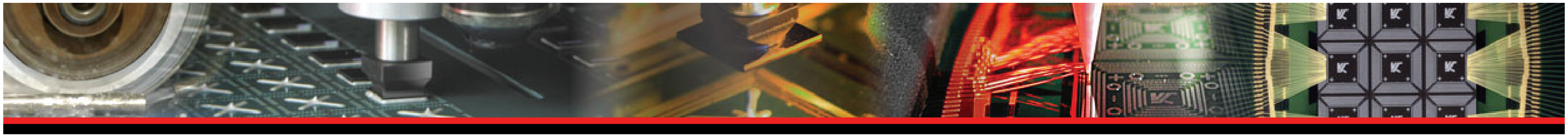
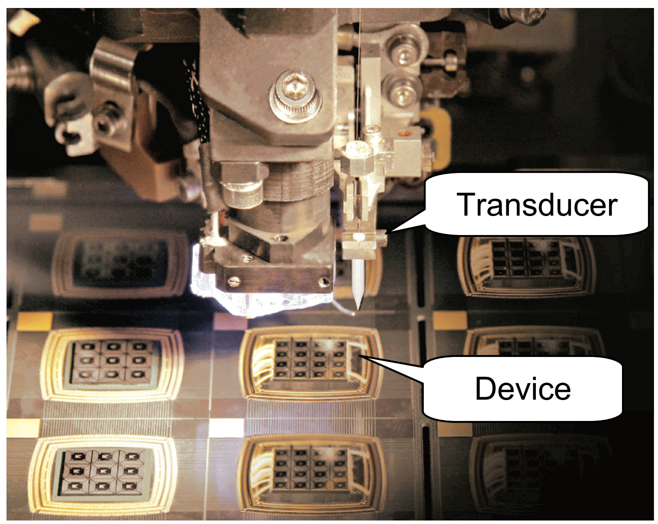


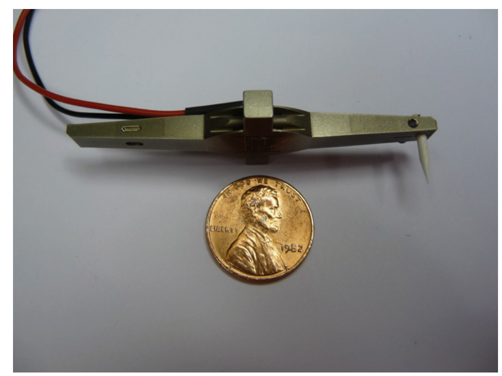
Optimizing Piezoelectric Crystal Preload in Ultrasonic Transducers

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
- Electromechanical Coupling
- Equivalent Circuits
- Bode Plot & Admittance Loop
- Experimental Results
- Conclusions
- References
- Questions

MOTIVATION FOR THE WORK

- Preload is Required to Maintain the Piezo Stack in Compression
- Most Often Integral Piezo Crystals Used as Force Sensor for Preload
- A Press Fixture w/ Charge Amp Measures Voltage vs. Force
- Method Inaccurate Since Crystal Properties Can Vary ±20% Lot-to-Lot
- Vendor Preload Guidelines Based on Static Crystal Testing Only
- Designers Often Struggle to Determine/Control Optimal Preload Level
- Transducer Based Methods and Metrics are Needed

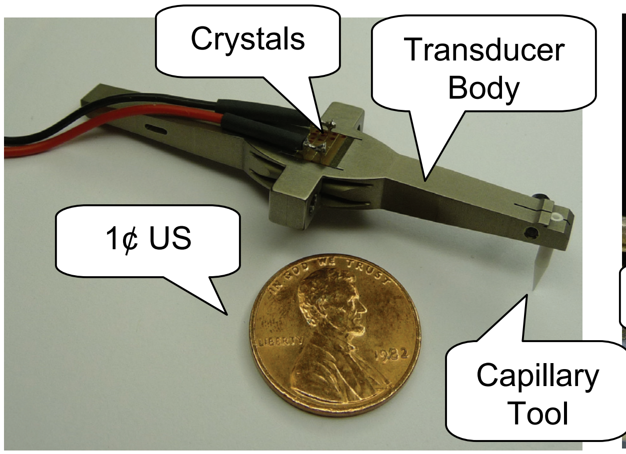
MOTIVATION CON'T

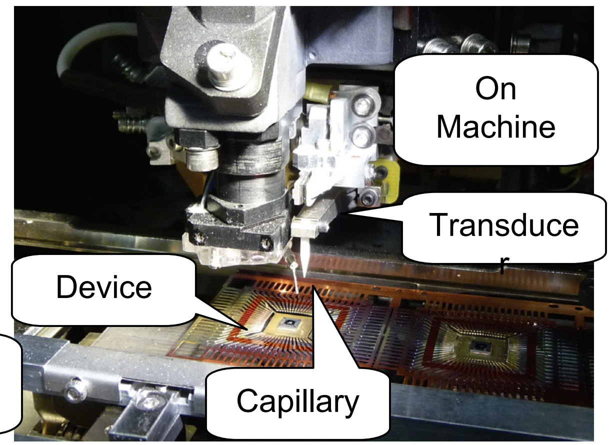
Why is Controlling Preload So Important?

- Inadequate Preload Results in Dynamic Gapping at Interfaces
- Dynamic Gapping Manifests as Higher Impedance, Heating, Etc.
- Inadequate Preload Results in Prolonged Stress-Aging Affects
- Excessive Preload Results in Pronounced Depolling
- Excessive Preload Produces Unstable Impedance and Aging with Use

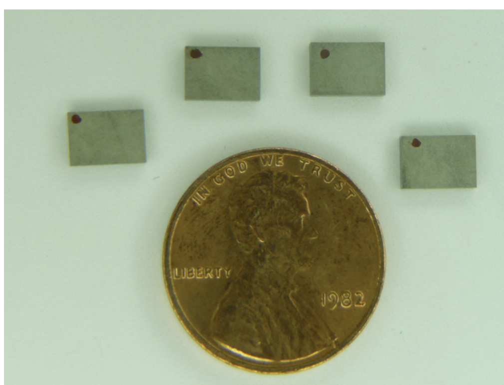
SPECIFIC TRANSDUCER APPLICATION

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

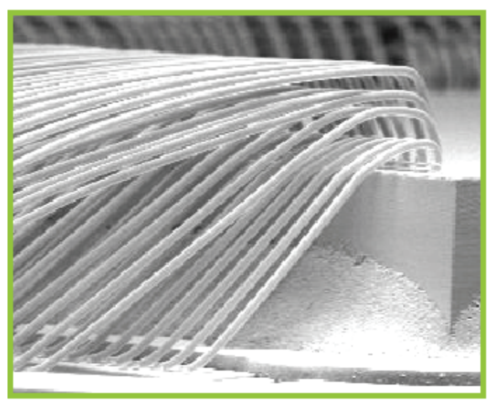




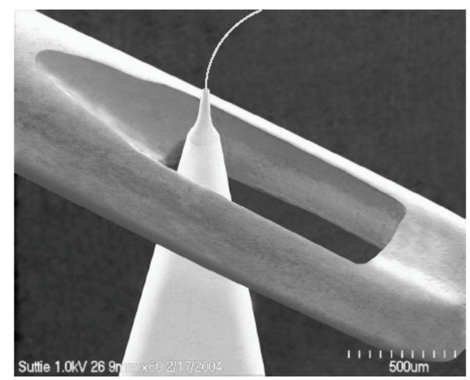
Transducer Specs
500 mA Max Current
120 kHz Operating Mode
80 Ohm Max Impedance
Operation 40 Bonds/Sec
Bond Duration ~10mSec
PZT8 Crystals (4X)



PZT8 Piezoelectric Crystals



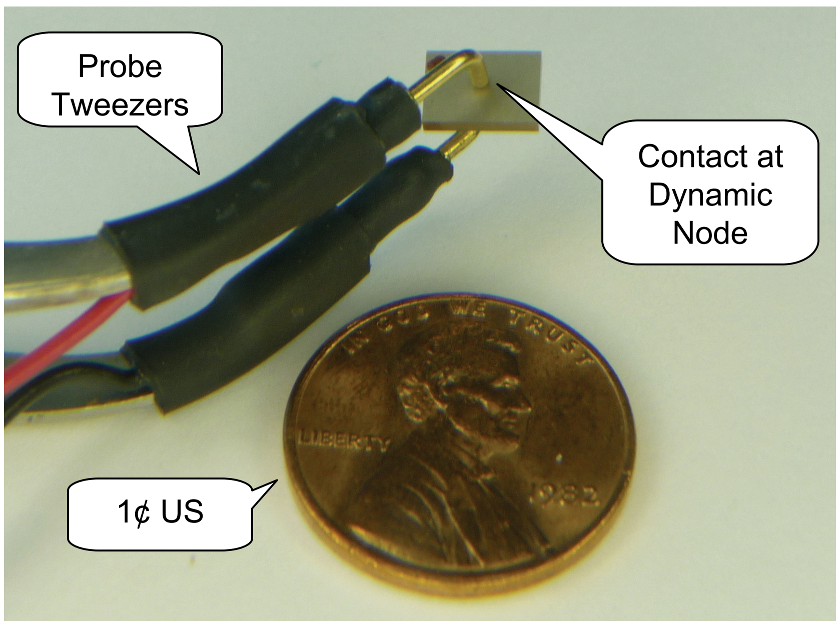
Actual Wire Bonds From of a Multi-Tier Package



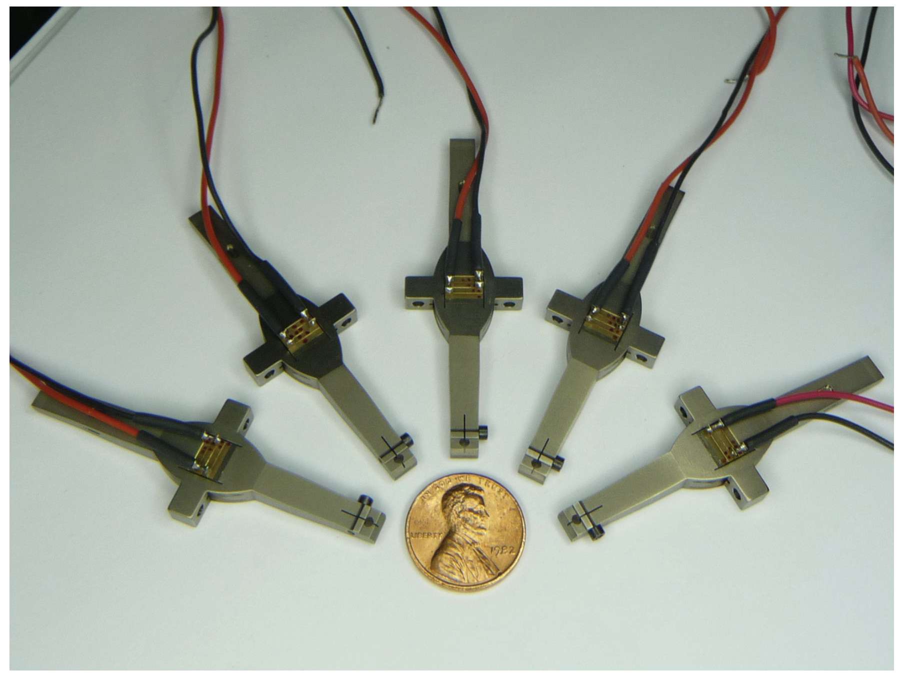
Typical Capillary Tool with Wire Compared to Sewing Needle

RESEARCH SUMMARY

- Five Transducers Built at Various Preload Levels from 4.5 ksi to 18 ksi
- All 5X Transducers Bodies and 20X Crystals from Same Production Lot
- Experimental Methods were Both Crystal and Transducer Based
- Transducers Subjected to Stabilizing Heat-Treatment & Cycling After Build



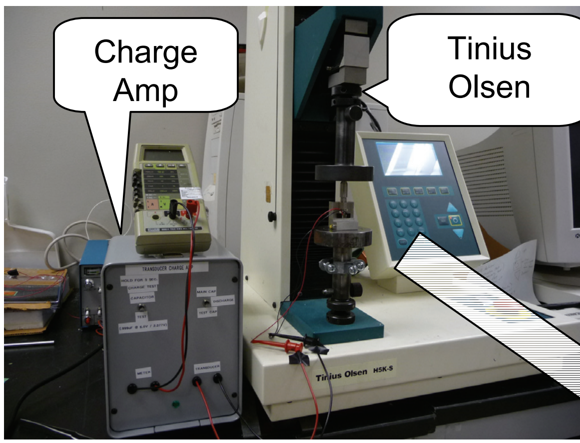
Crystal Based Bode Plot Technique

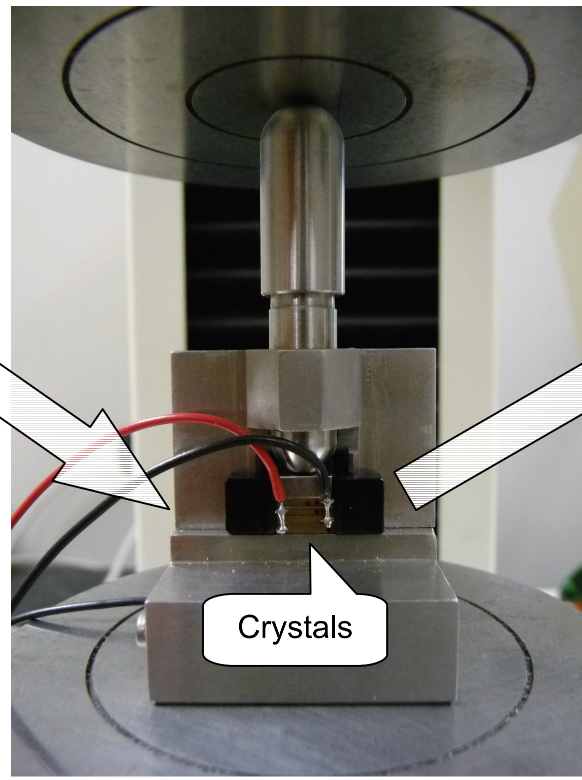


The Five Transducers Build for the Study

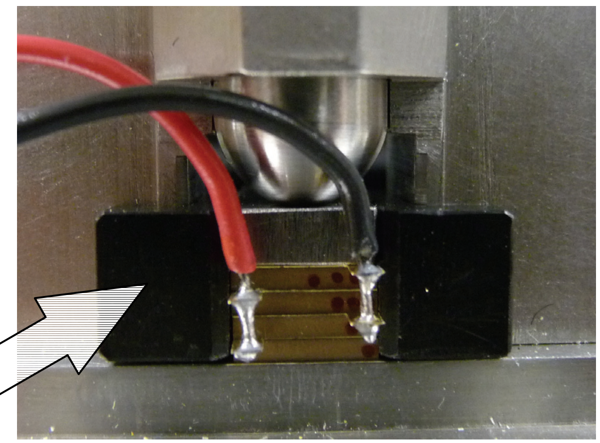
EXPERIMENTAL METHODS & METRICS

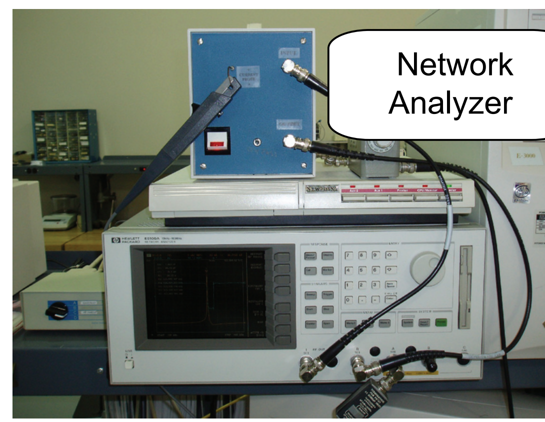
- Bode Plots, Cap, DF of Individual Crystals Before Build
- Calibrated Stack Voltage vs. Force Prior to Assembly
- Bode Plots, Cap, DF of Transducer After Build and Heat-Treat
- Laser Vibrometer Gain Measurements After Heat-Treatment & Cycling





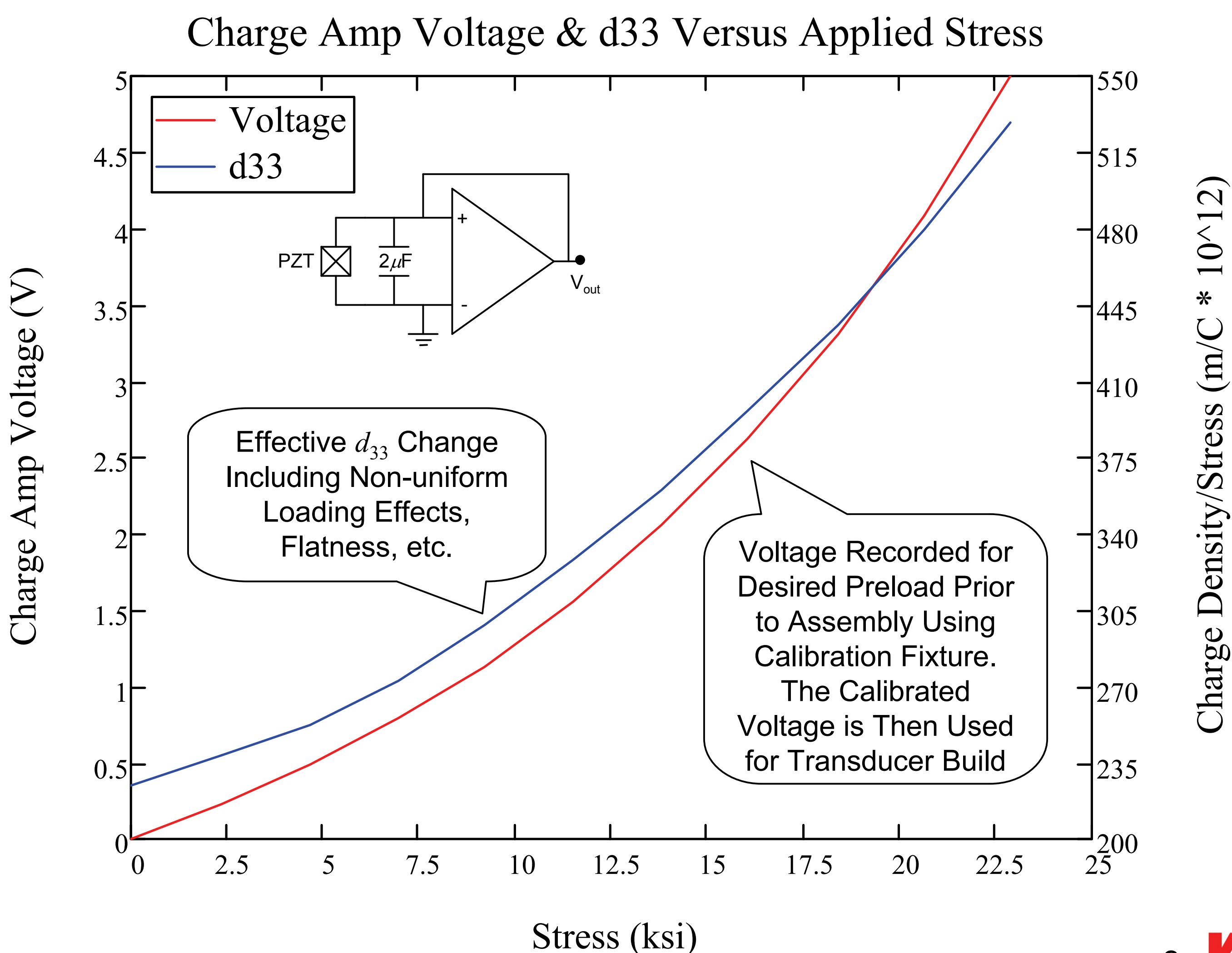
Crystal Voltage vs. Force Calibration Fixture (Before Assembly)





METHODS & METRICS CON'T

- Results from Voltage vs. Force Calibration Fixture
- Piezoelectric Constant d_{33} Increases with Applied Stress



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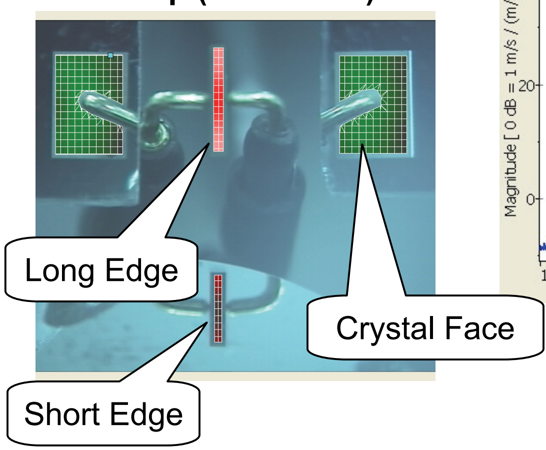
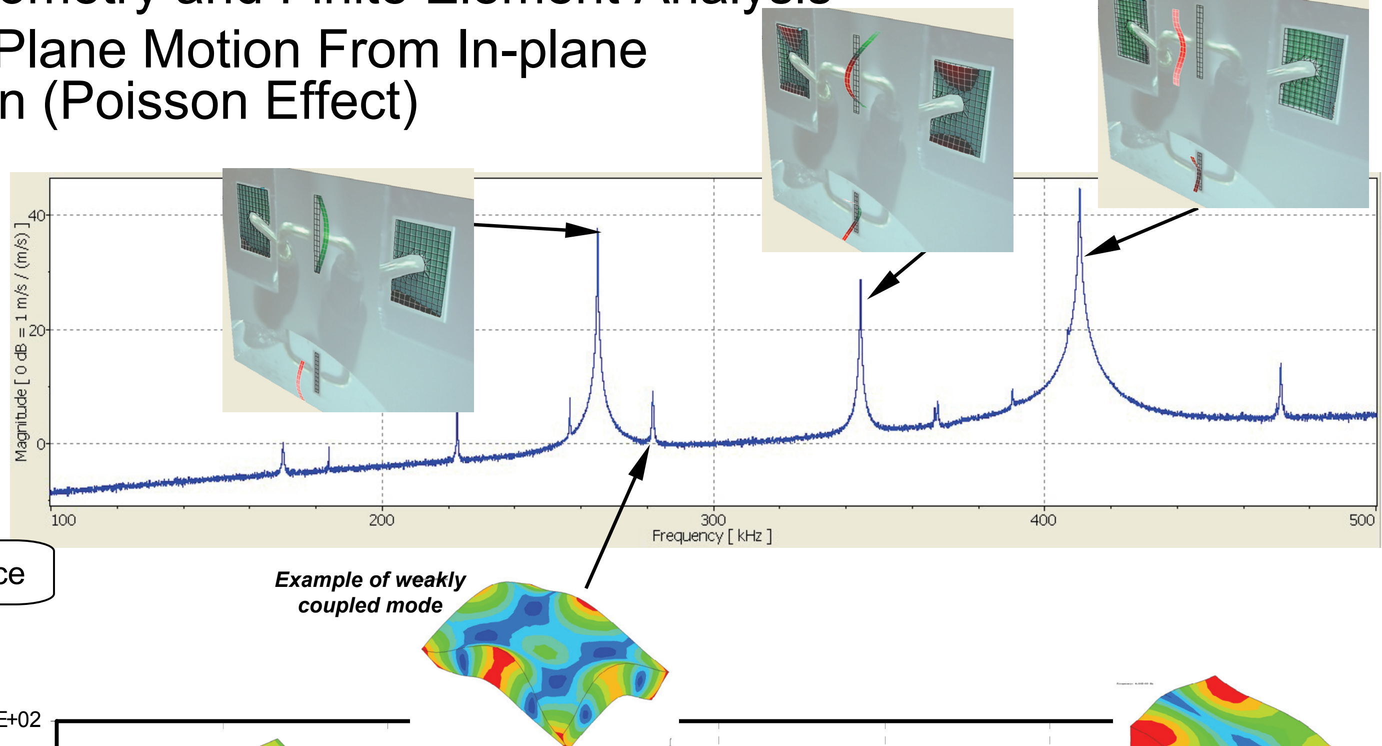
METHODS & METRICS CON'T

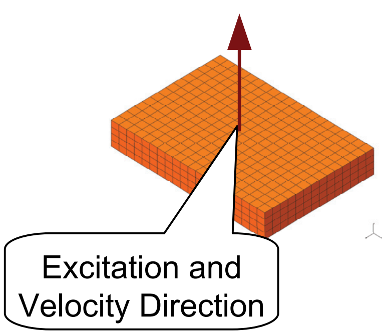
- Crystal Laser Vibrometry and Finite Element Analysis
- Measured Out-of-Plane Motion From In-plane Structural Vibration (Poisson Effect)

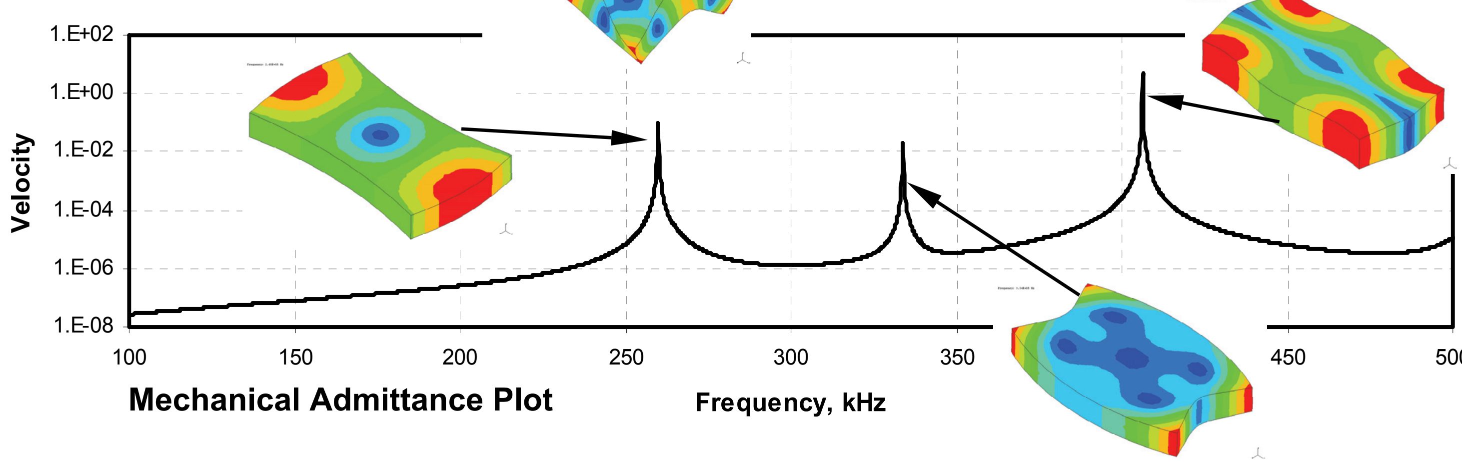
Single Crystal Vibrometer Setup (3X Mirrors)





Finite Element Model

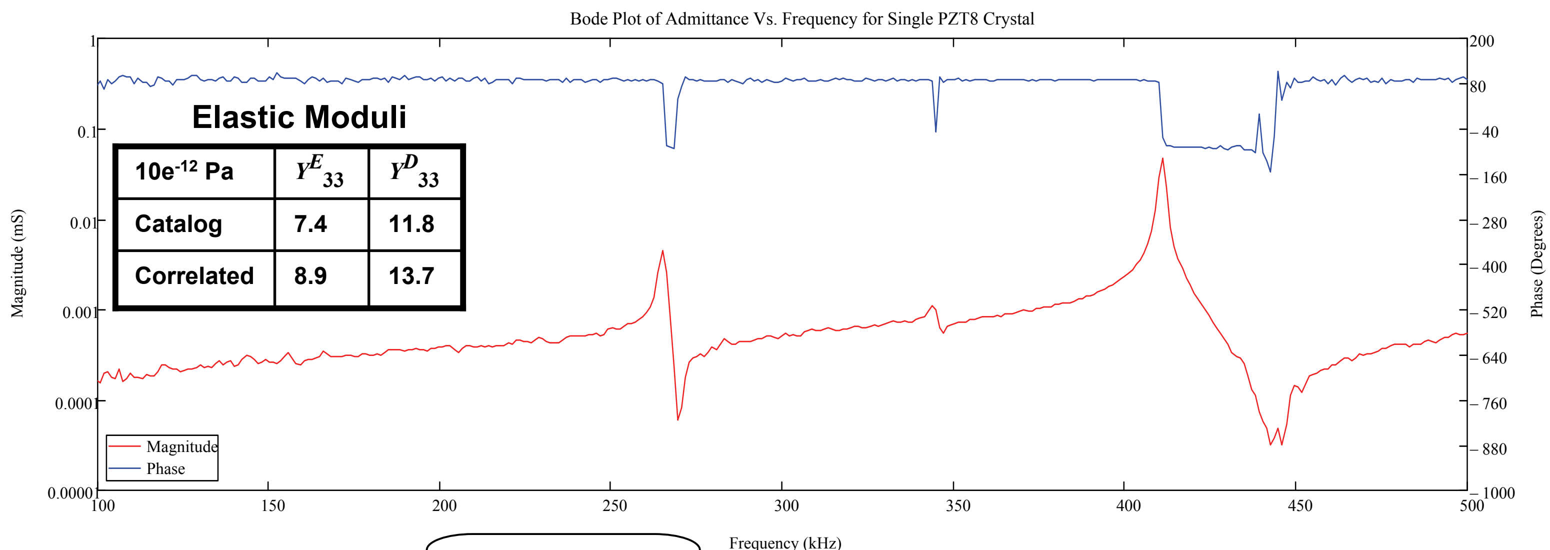




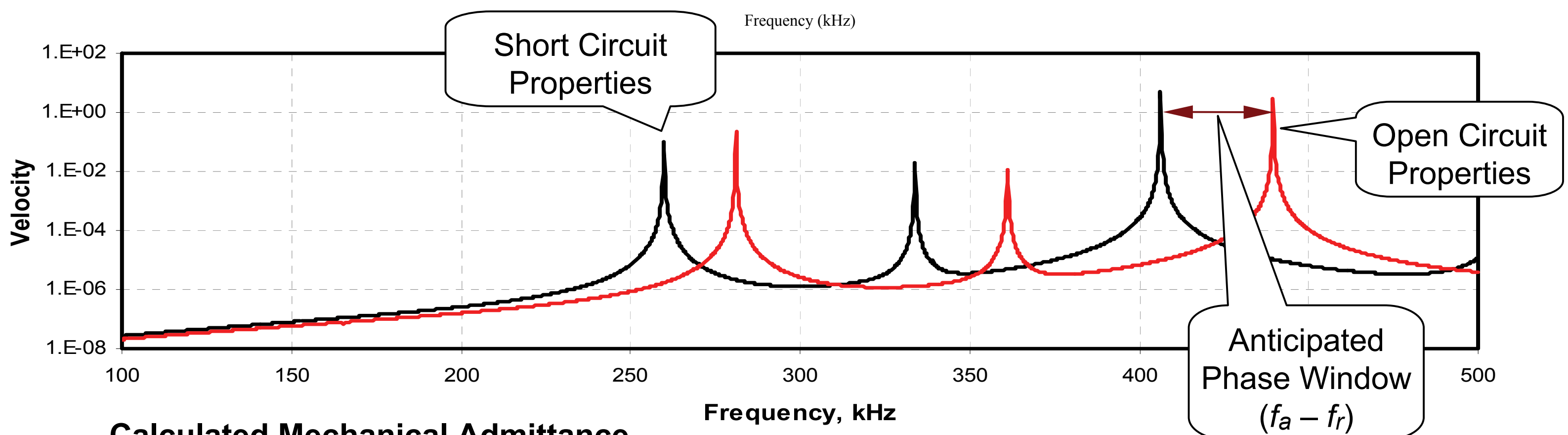
METHODS & METRICS CON'T

- Bode Plot and Corresponding Finite Element Admittance
- Single Crystal Analysis Demonstrates Short and Open Circuit Properties

Typical Bode Plot of Admittance Vs. Frequency of Single PZT8 Crystal



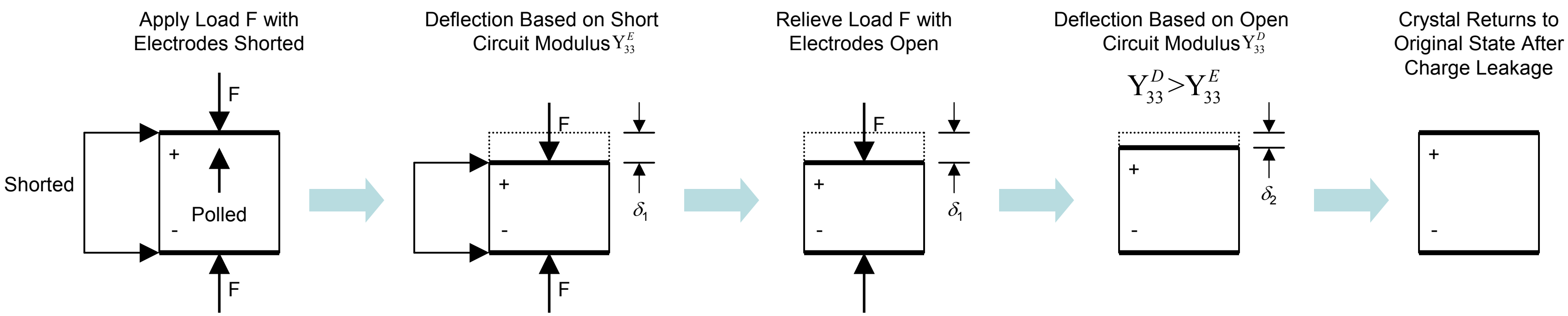
10e^{-12} Pa	Y^E_{33}	Y^D_{33}
Catalog	7.4	11.8
Correlated	8.9	13.7

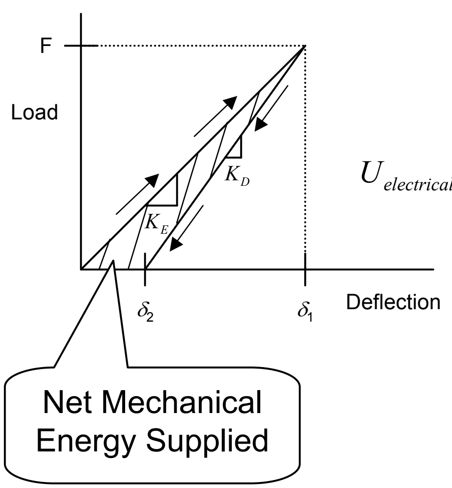


Calculated Mechanical Admittance

ELECTROMECHANICAL COUPLING k_{33}

- k_{33} Varies Proportionally to d_{33}, But Inversely to Square Root of Permittivity
- k_{33} Varies Proportionally to Delta Between Open and Short Circuit Moduli





$$U_{mechanical} = \frac{1}{2} K_E \delta_1^2 - \frac{1}{2} K_D \left(\delta_1 - \delta_2\right)^2 \qquad K_D = Y_{33}^{D} \frac{Area}{Thickness} \qquad K_E = Y_{33}^{E} \frac{Area}{Thickness}$$

$$U_{electrical} = \frac{1}{2} C V^2 \qquad C = \varepsilon_{33}^{T} \frac{Area}{Thickness} \qquad V = \frac{F}{d_{33} K_D} \qquad k_{33} = \sqrt{\frac{Electrical\ Energy\ Stored}{Mechanical\ Energy\ Supplied}} = \sqrt{\frac{U_{electrical}}{U_{mechanical}}}$$

$$k_{33} = d_{33} Y_{33}^{D} \sqrt{\frac{Y_{33}^{D} - Y_{33}^{E}}{Y_{33}^{E} \varepsilon_{33}^{T}}}$$

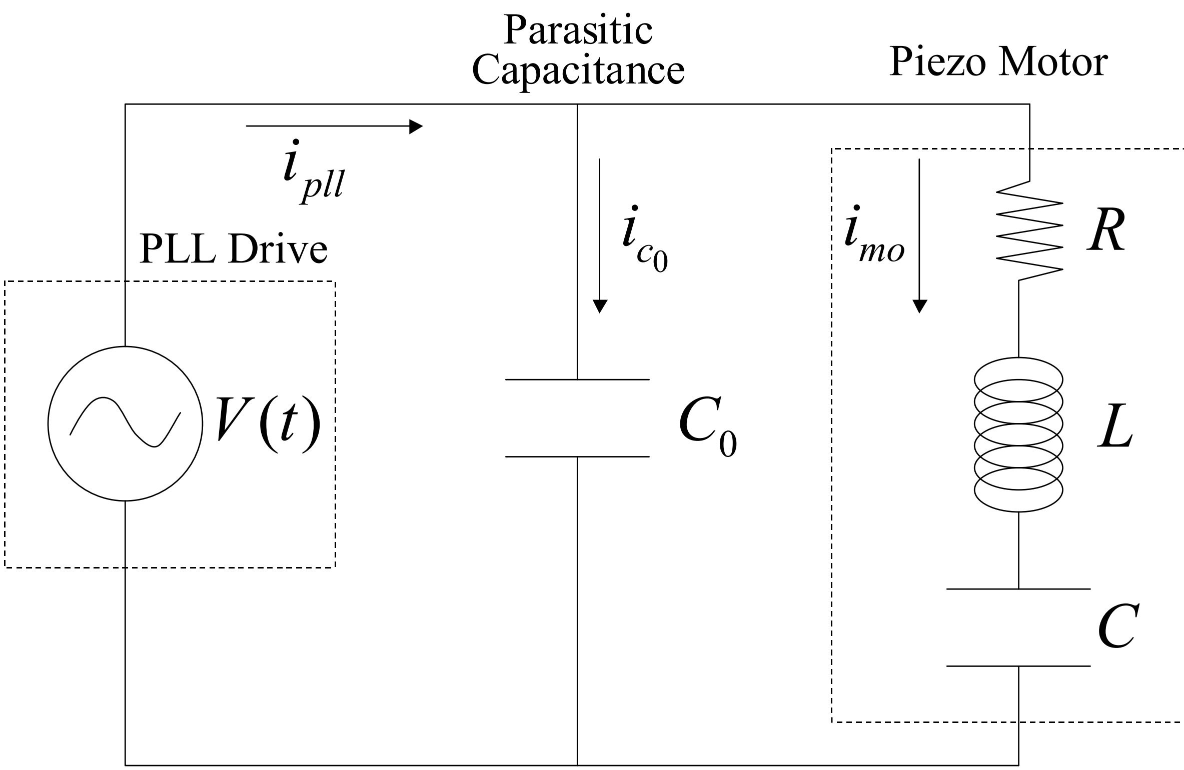
$$k_{33} = .63 \quad (\mathrm{PZT8})$$

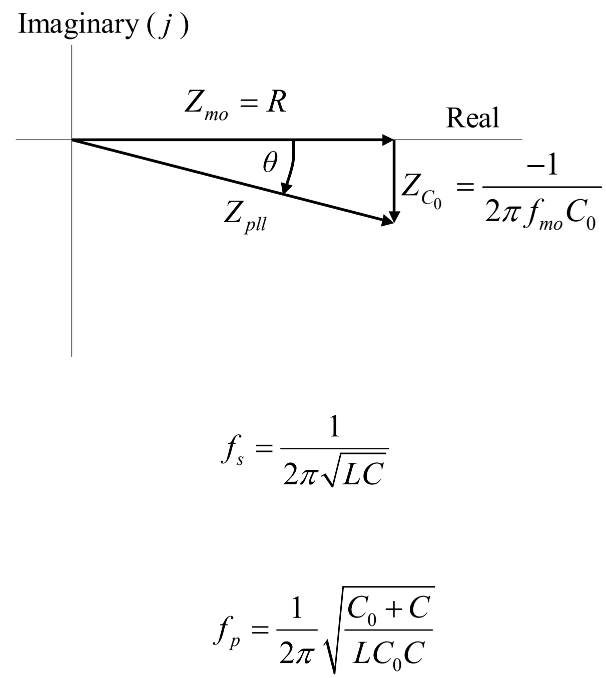
Proportional

Inversely

EQUIVALENT CIRCUITS

- For f_s Series Resonance $i_{pll} \approx i_{mo}$ and $i_{pll} >> i_{co}$ (Via Short Circuit Modulus)
- For f_p Parallel Resonance $i_{co} \approx -i_{mo}$ and $i_{pll} << i_{mo}$ (Via Open Circuit Modulus)
- Spacing of f_p - f_s Proportional to Delta Between $Y_{33}^{D} - Y_{33}^{E}$ (And k_{33} Too)





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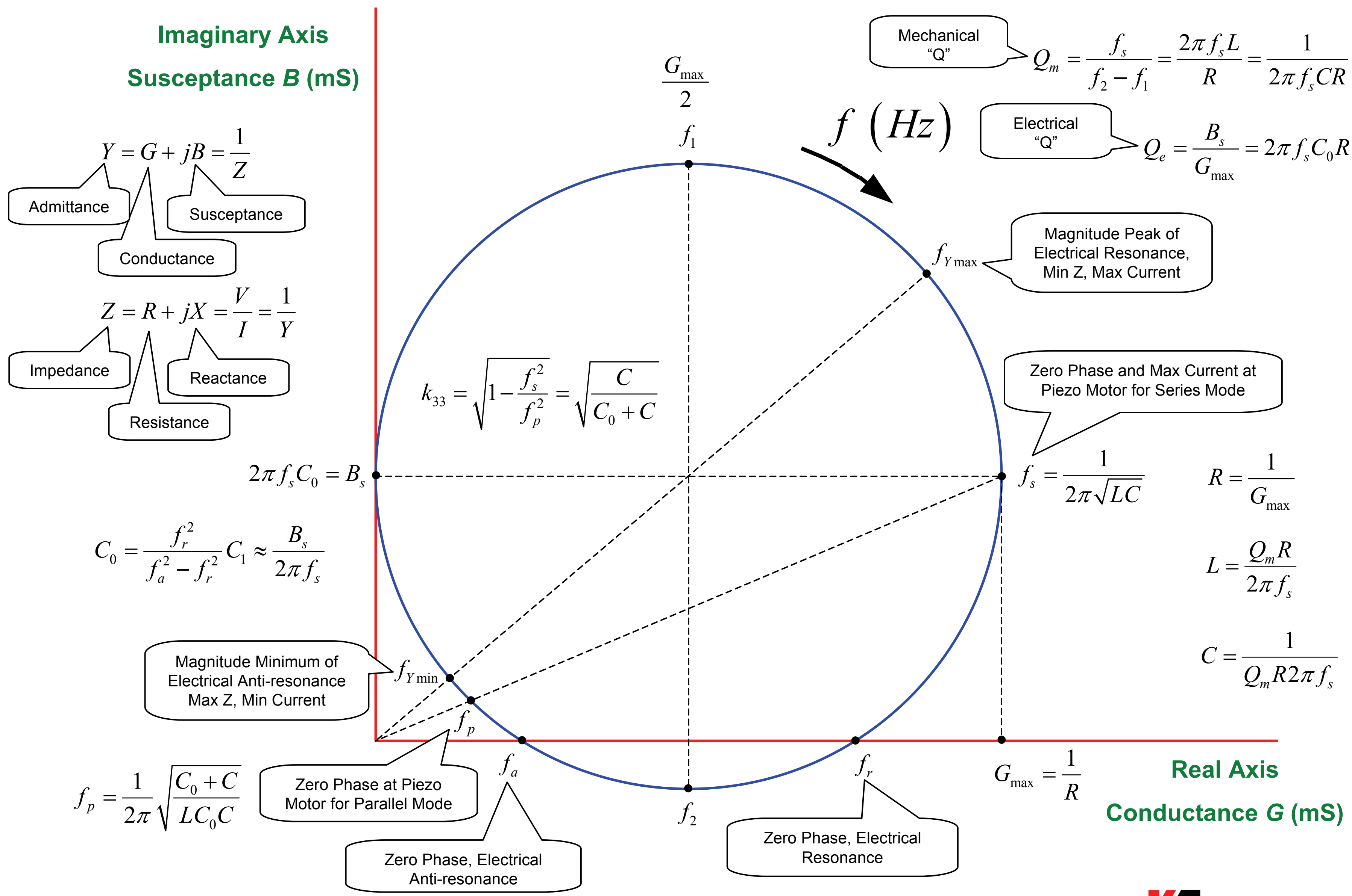
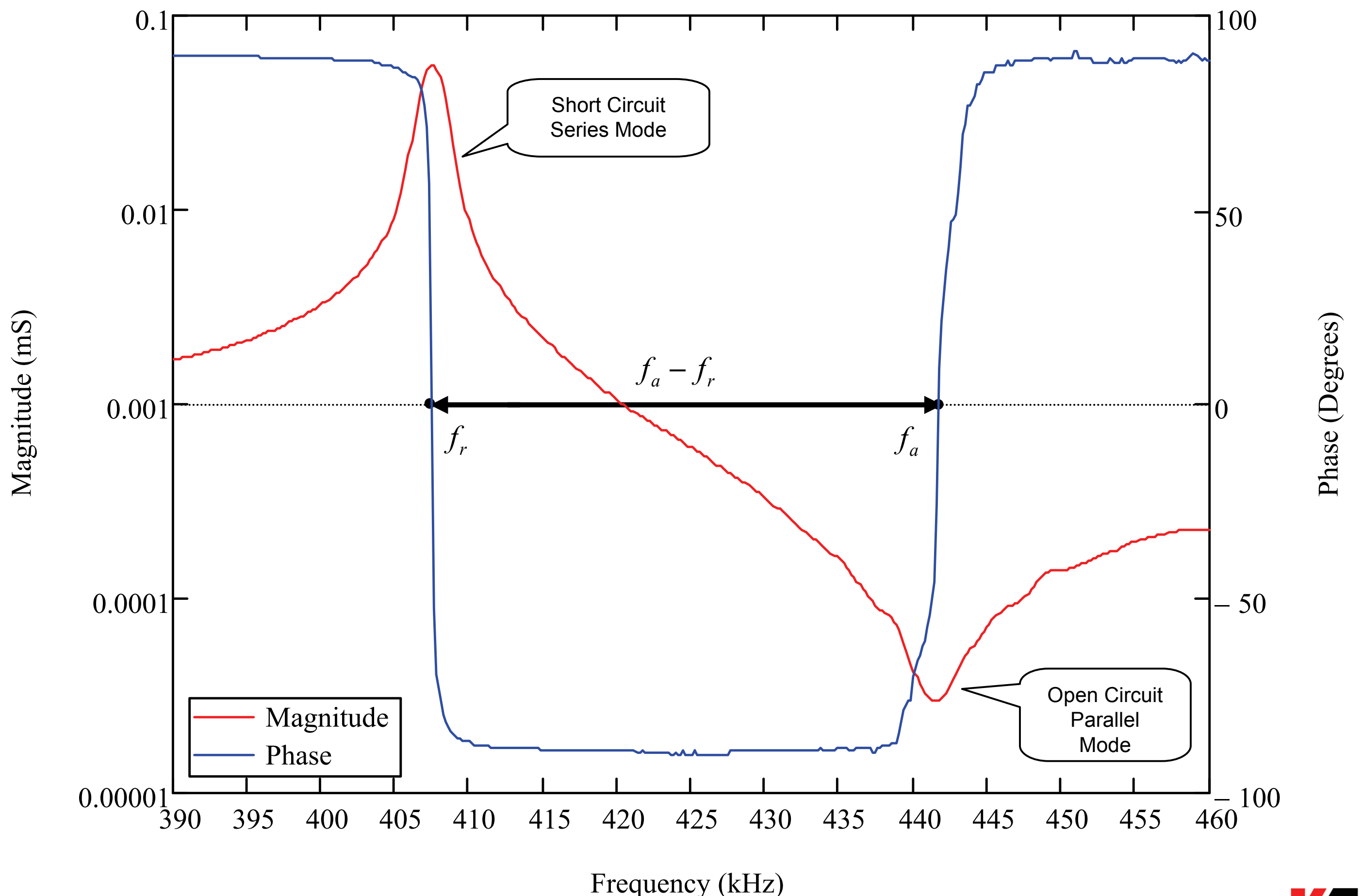
ADMITTANCE (Y) LOOP



EXPERIMENTAL RESULTS

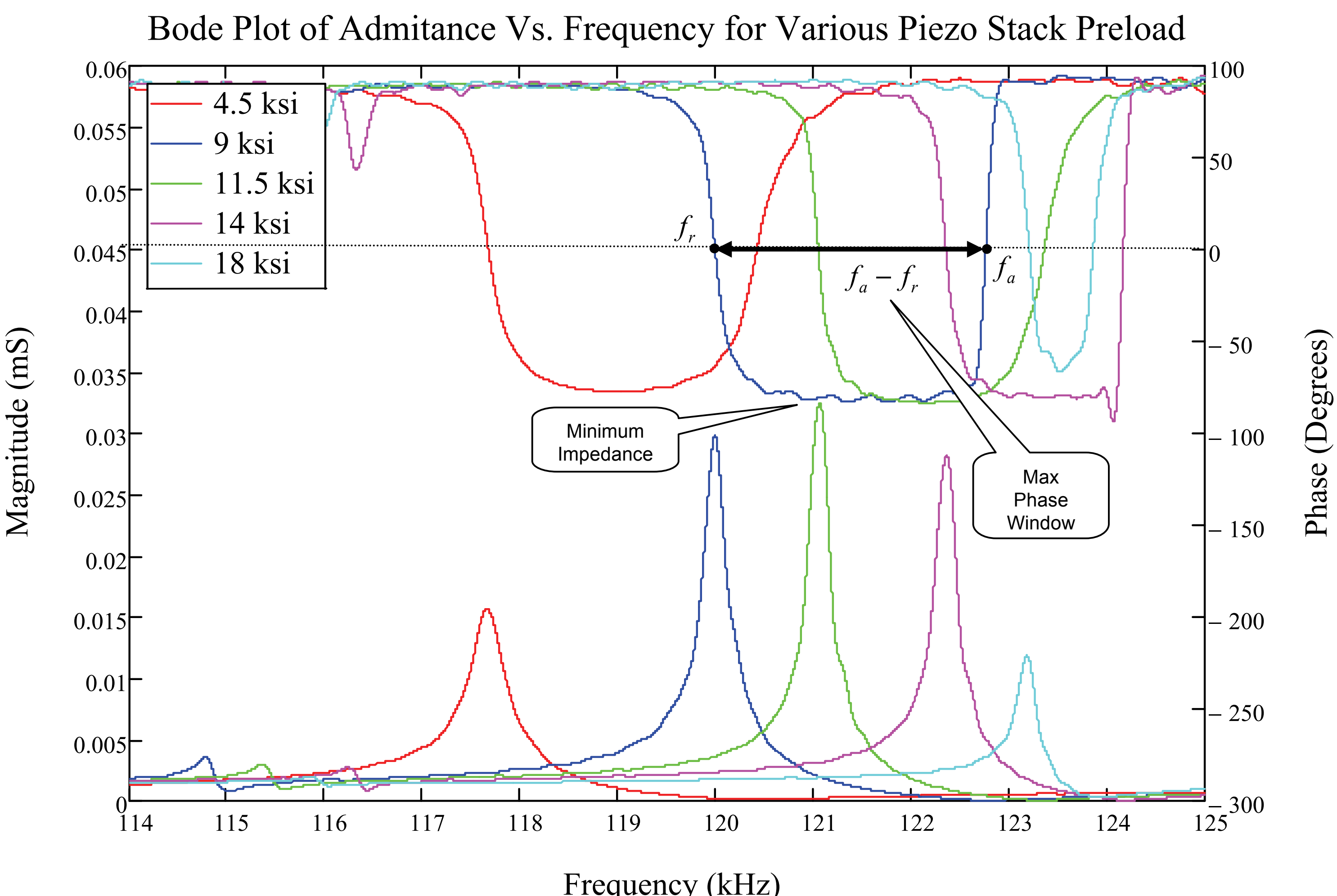
- Typical Single Free-Free Crystal Bode Plot Results Prior to Build
- k_{33} Proportional to Phase Window $f_a - f_r$ (Similar for All Crystals)
- Dissipation Factor DF was .004 for All Crystals (Tanδ)

Bode Plot of Admittance Vs. Frequency for Single PZT8 Crystal



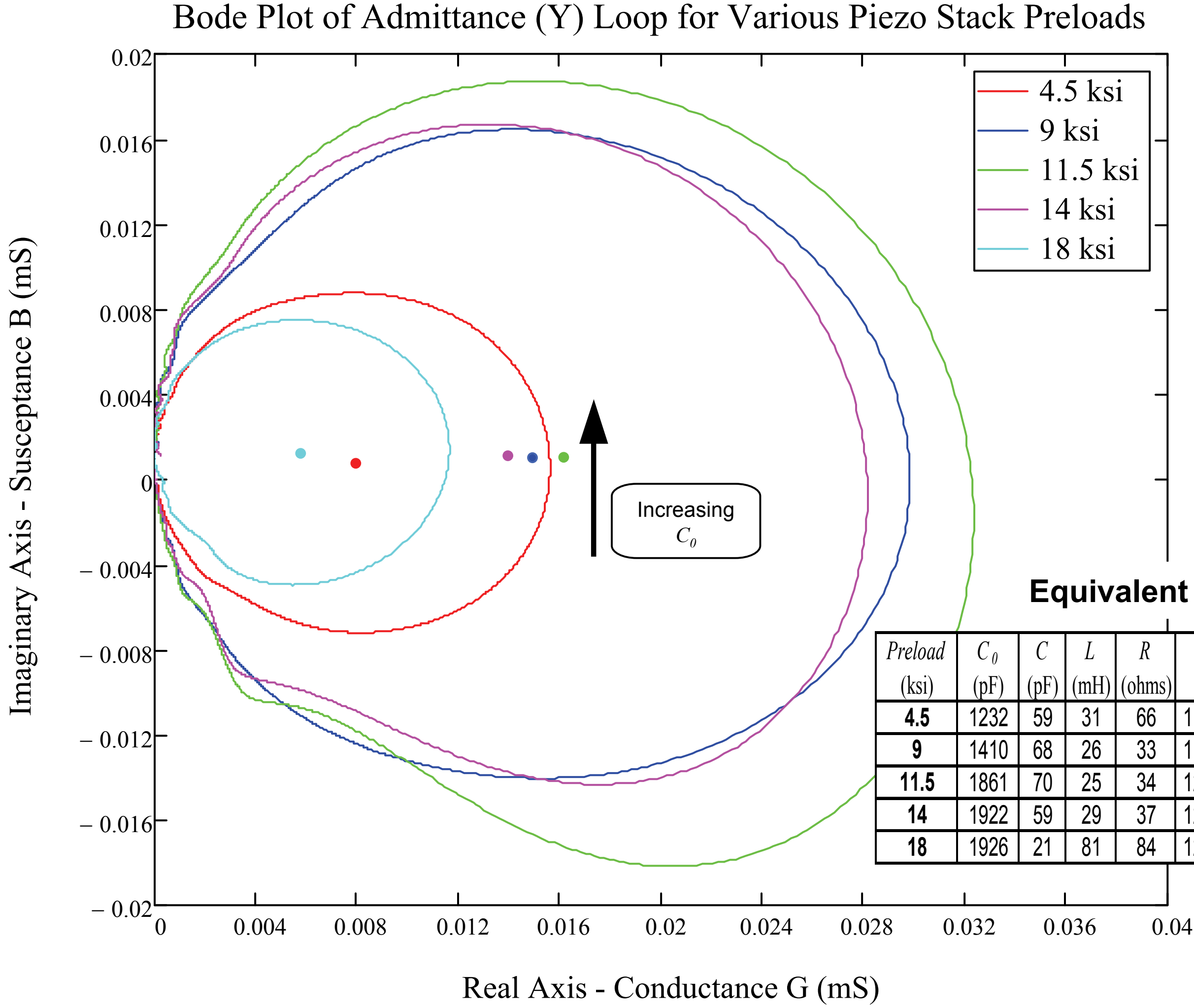
EXPERIMENTAL RESULTS CON'T

- Transducer Bode Plot Results After Stabilizing Heat-Treatment
- k_{33} Proportional to Phase Window $f_a - f_r$



EXPERIMENTAL RESULTS CON'T

- Transducer Admittance Loop Bode Results After Stabilizing HT
- Find Preload that Maximizes k_{33} and Q_m, but Minimizes Q_e



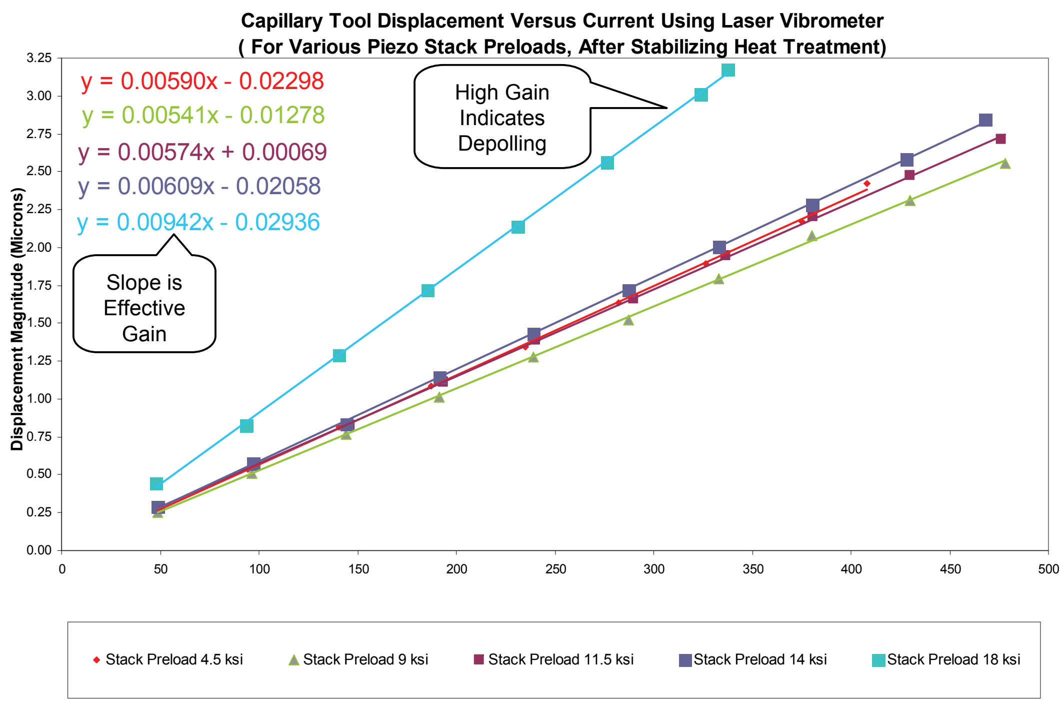
Maximize k_{33}
Maximize Q_m
Minimize Q_e

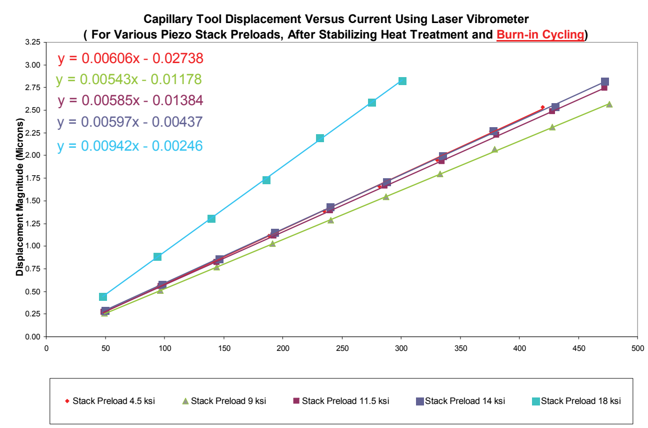
Equivalent Circuit Properties

Preload (ksi)	C_0 (pF)	C (pF)	L (mH)	R (ohms)	f_s (kHz)	f_a (kHz)	f_r (kHz)	f_1 (kHz)	f_2 (kHz)	f_p (kHz)	k_{33}	Q_m	Q_e
4.5	1232	59	31	66	117.678	120.433	117.671	117.510	117.846	120.444	0.2130	350	0.060
9	1410	68	26	33	119.988	122.857	119.985	119.885	120.091	122.548	0.2145	582	0.035
11.5	1861	70	25	34	121.065	123.313	121.055	120.957	121.173	123.334	0.1905	560	0.047
14	1922	59	29	37	122.370	124.241	122.367	122.267	122.473	124.234	0.1730	594	0.055
18	1926	21	81	84	123.192	123.878	123.220	123.110	123.275	123.861	0.1029	747	0.125

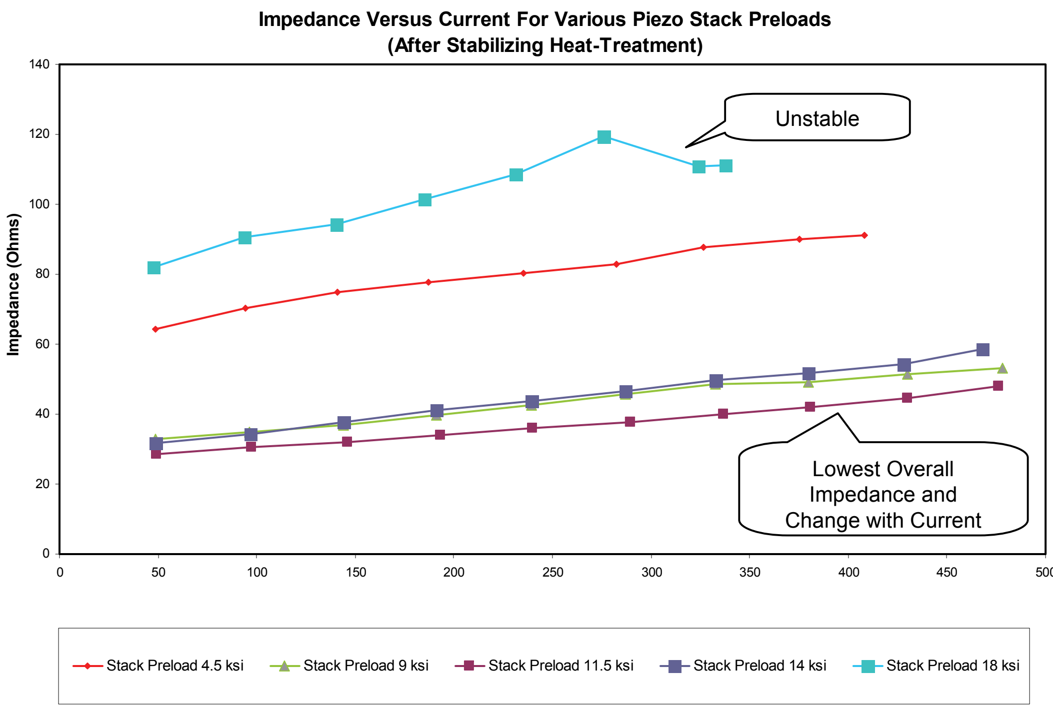
EXPERIMENTAL RESULTS CON'T

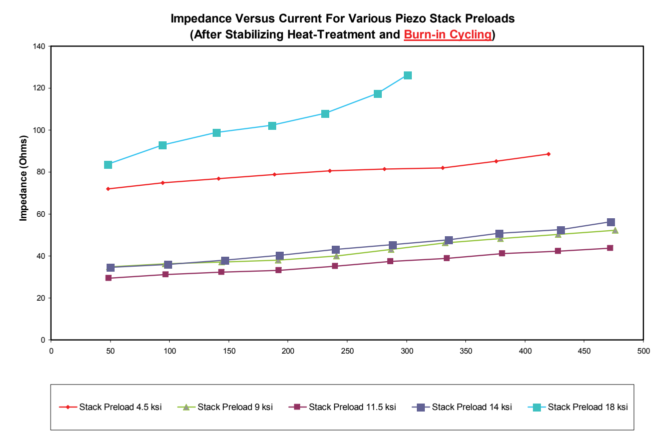
- Tool Displacement to Current Gain Results After Stabilizing HT & Cycling





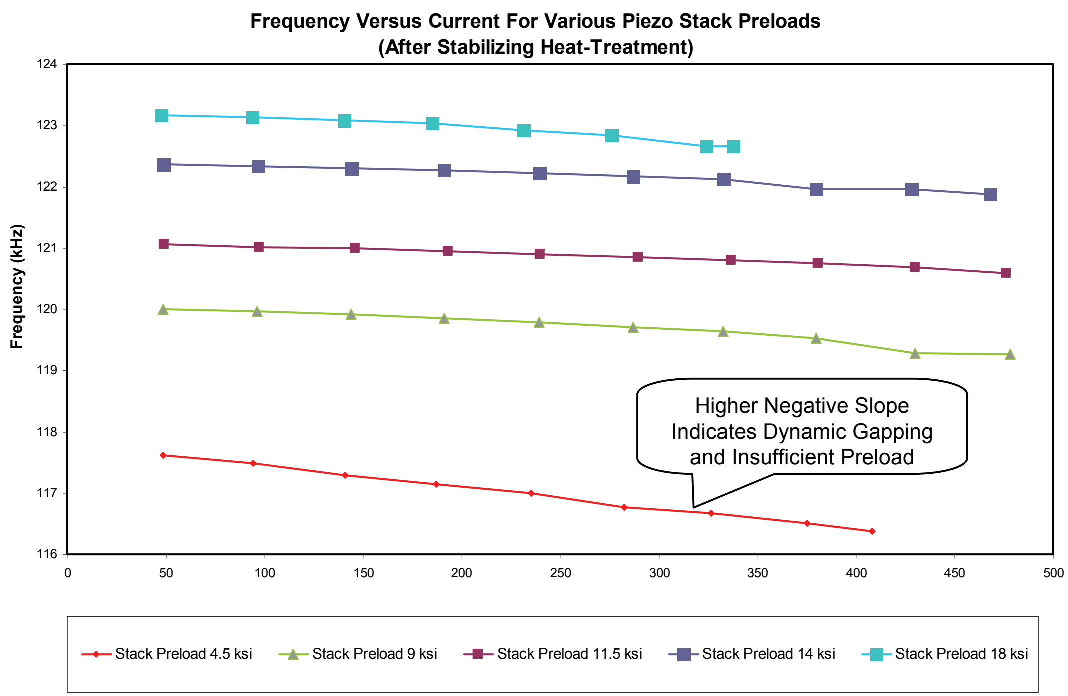
- Impedance Vs. Current Results After Stabilizing Heat-Treatment & Cycling

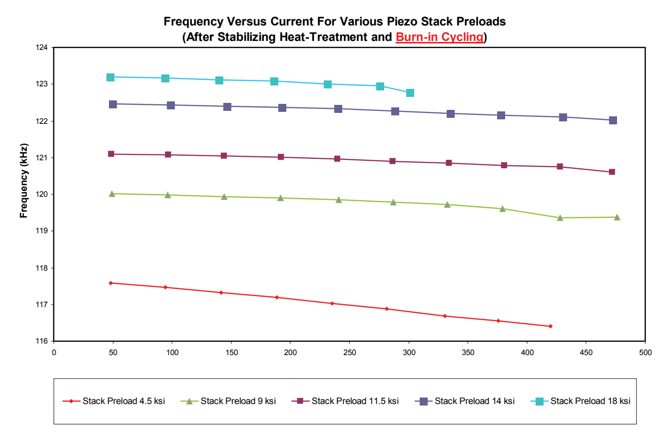




EXPERIMENTAL RESULTS CON'T

- Frequency Vs. Current Results After Stabilizing Heat-Treatment & Cycling





CONCLUSIONS

- Optimal Preload Range for PZT8 Found From 9 to 14 ksi (11.5 ksi Best)
- Design Methodology Presented for Optimizing Transducer Preload
- Insufficient Preload Causes High Impedance and Dynamic Gapping
- Excessive Preload Causes Severe Depolling and High Impedance
- Stress Related Aging Affects Minimized at Higher Preloads
- New Preload Method Using Calibrated Stack Voltages Presented
- Bode Plot Method for Individual Crystals Presented

REFERENCES

- Stansfield D., *Underwater Electroacoustic Transducers*, Peninsula Publishing, CA, 1991

- Wilson, O.B., *Introduction to Theory and Design of Sonar Transducers*, Peninsula Publishing, CA, 1991

- Sherman, C.H., Butler, J.L., *Transducers and Arrays for Underwater Sound*, Springer, NY, 2007

QUESTIONS