Transducer Control Algorithms

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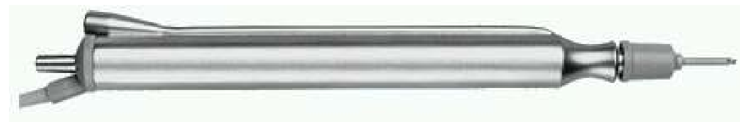
Background

Need to precisely control the velocity (displacement) of ultrasonic tools (end effectors)

- Velocity Control of High Q Transducers
  - Operating at or close to resonance F_R

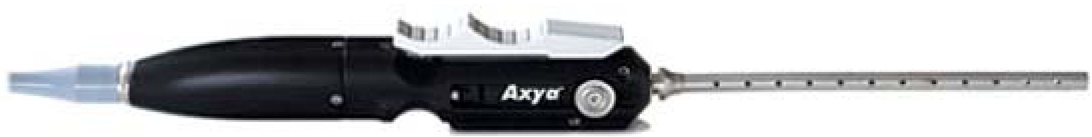
    For Example:



Ultrasonic “jack-hammer” handpiece for cataract removal (Phacoemulsification)

- Velocity Control of Low Q Transducers
  - Operating at or close to Anti-resonance F_A

    For Example:



Axya ultrasonic suture welding handpiece

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Scope of this Presentation

- Piezoelectric Ceramic Aging and Stability
  - The medical environment
- Novel Simple Method of Velocity Control
  - Compensates for changes in piezo properties that occur during operational use
  - Applicable for control algorithms based on constant current
    - High Q transducers operating at or close to F_R
- Comparison of Operational Performance at F_R and F_A
  - Control based on constant current @ F_R versus constant voltage @ F_A
  - Computer model and practical experiments

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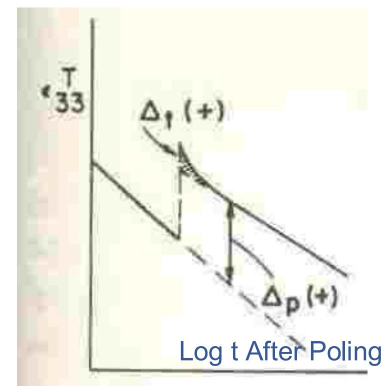
Changes in Piezo Properties (All Transducers)

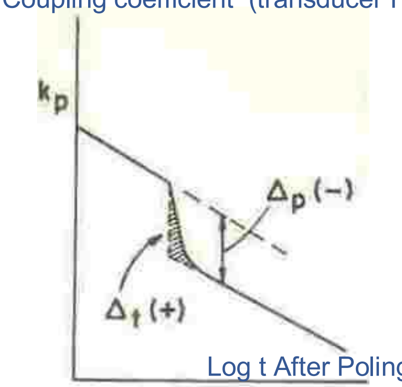
Piezo Aging & Stability (Berlincourt Illustrations)

- Permanent Changes Δ p
  - Aging approximately logarithmic in nature
- Temporary Changes Δ t
  - Exposure to mechanical stress, high electric field, or elevated temperature
  - Permanent and temporary changes have same sign (+) for permittivity
  - For coupling coefficient the permanent change is (–) and the temporary change is (+)

Material Permittivity (transducer capacitance)



Material Coupling coefficient (transducer Fa - Fr)



Changes in Piezo Properties (Medical Transducers

Langeven style subjected to multiple steam sterilization cycles

- Permanent Changes Δ p
  - Combined effects of autoclave temperature (137°C) and bias stress
  - Extrapolated from measured Navy Type I data (Krueger 1961)

Piezo Bias Stress (MPa)	25	35	45	55	65
Fraction of initial d_{33} value	.9	.85	.77	.70	.65
Fraction of initial K^T_{33} value	1.04	1.06	1.08	1.10	1.12

- Temporary Changes Δ t
  - Immediately after a 137°C autoclave cycle (cold water rapid cool down)
    - Navy Type III piezo with nominal 30 MPa bias stress
    - Coupling coefficient k increased by 5.2 %
    - Dielectric constant (capacitance) increased by 16%

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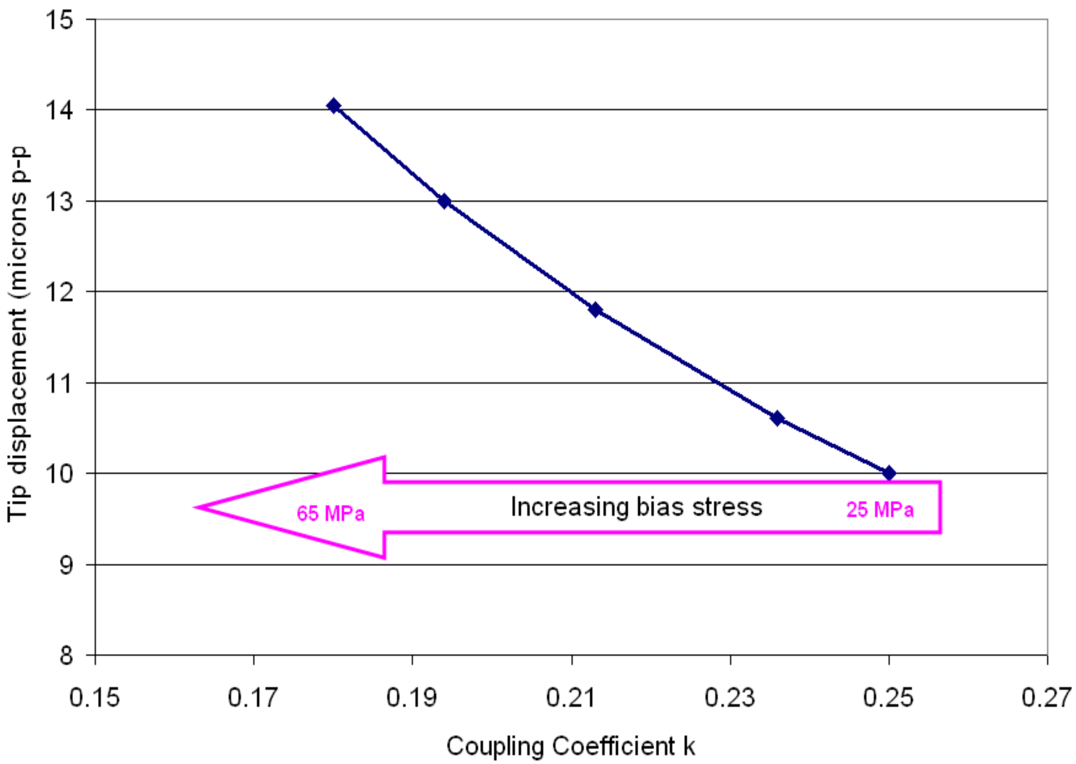
Computer Model Effects of Permanent Changes

PiezoTran (based on acoustic transmission line theory)

Illustrative example: Black and Decker Buzz Ultrasonic Stain Removal Transducer



Model Input:

- Voltage adjusted to maintain a constant current = 200 mA r.m.s.

Model Output

- Resonant frequency increases from approximately 51 kHz to 52 kHz as bias stress is increased

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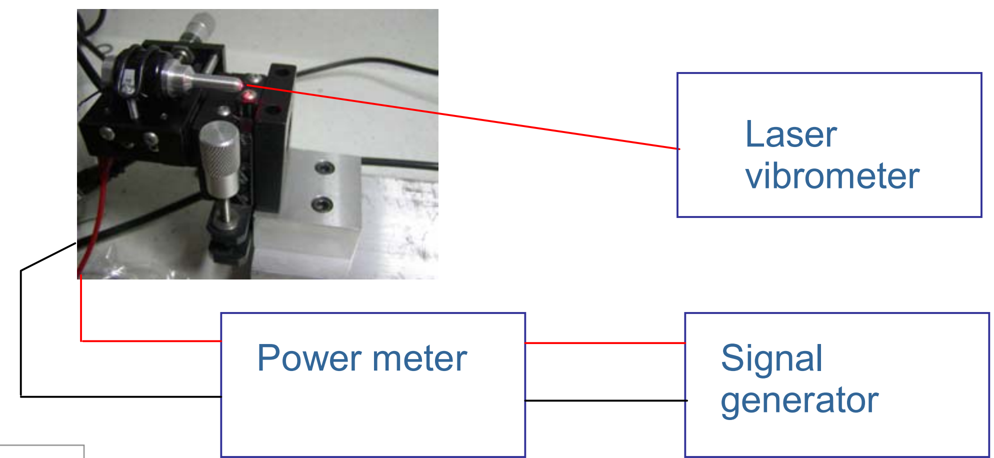
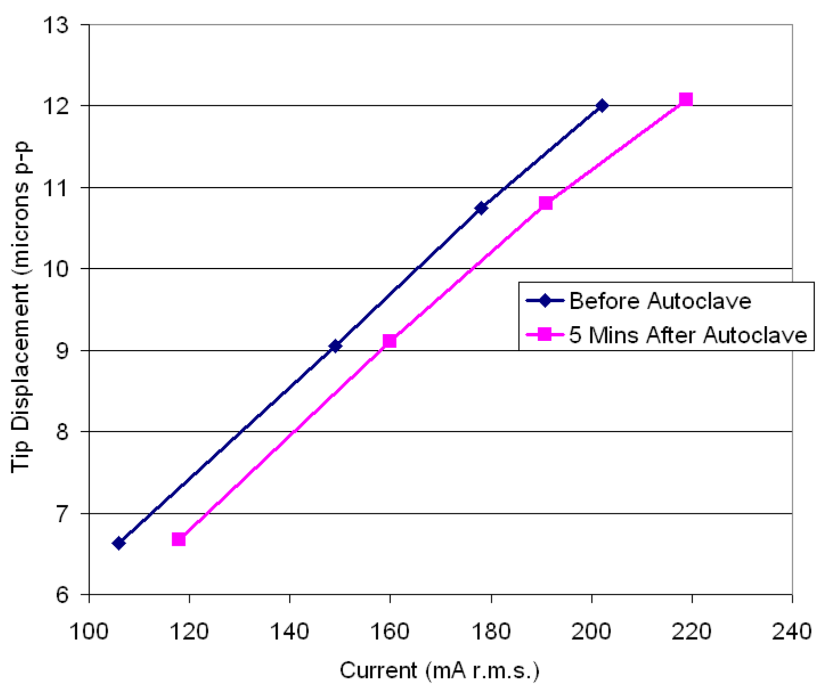
Measure Temporary Changes

as a result of a steam sterilization cycle

Measurement Method



Measured Data



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Evolving a Method of Velocity Control

- Assumptions
  - Constant current
  - Operating close to the resonance frequency
- Observations
  - Tip velocity increases as piezo properties are degraded by:
    - Age, Bias stress and High temperature cycles
  - The increase in velocity is inversely proportional to coupling coefficient (k_{eff})
- Implementation
  - Apply a correction factor based on a measured value of (k_{eff})
    - Measure / calculate k_{eff} immediately prior to, and during operational use

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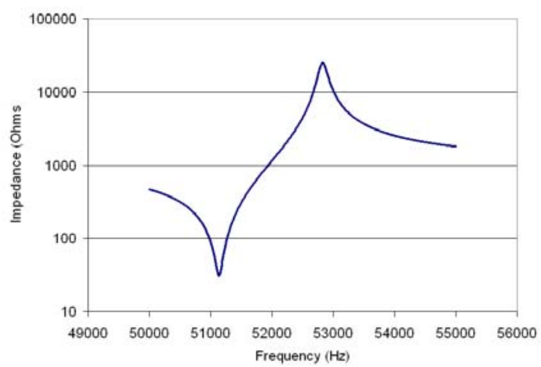
Methods of Measuring K_{eff}

- Based on the Resonant Characteristic F_R and F_A



$$k = \sqrt{1 - \left(\frac{F_r}{F_a}\right)^2}$$

$$k \approx \sqrt{\frac{2(F_a - F_r)}{F_r}}$$

- Complex System Control Algorithm
  - Frequency sweep from below resonance to above anti-resonance
  - Determine maximum and minimum impedance
  - Compute k_{eff} and apply current correction factor

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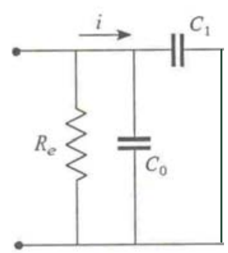
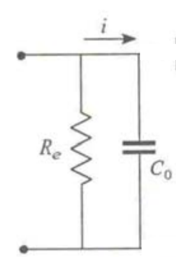
Methods of Measuring K_{eff}

- Based on the "Clamped" Non-motional Characteristic

Equivalent circuit at low frequency



Equivalent circuit at high frequency



$$k = \sqrt{\frac{C_1}{(C_0 + C_1)}}$$

- Mole's Method
  - Based on measuring capacitance above and below resonance
  - Calculated by substituting in the formula:

$$k = \sqrt{\frac{C_A - C_B}{\alpha(C_A + C_B)}}$$

  - Correction factor required for transducers with high gain horns

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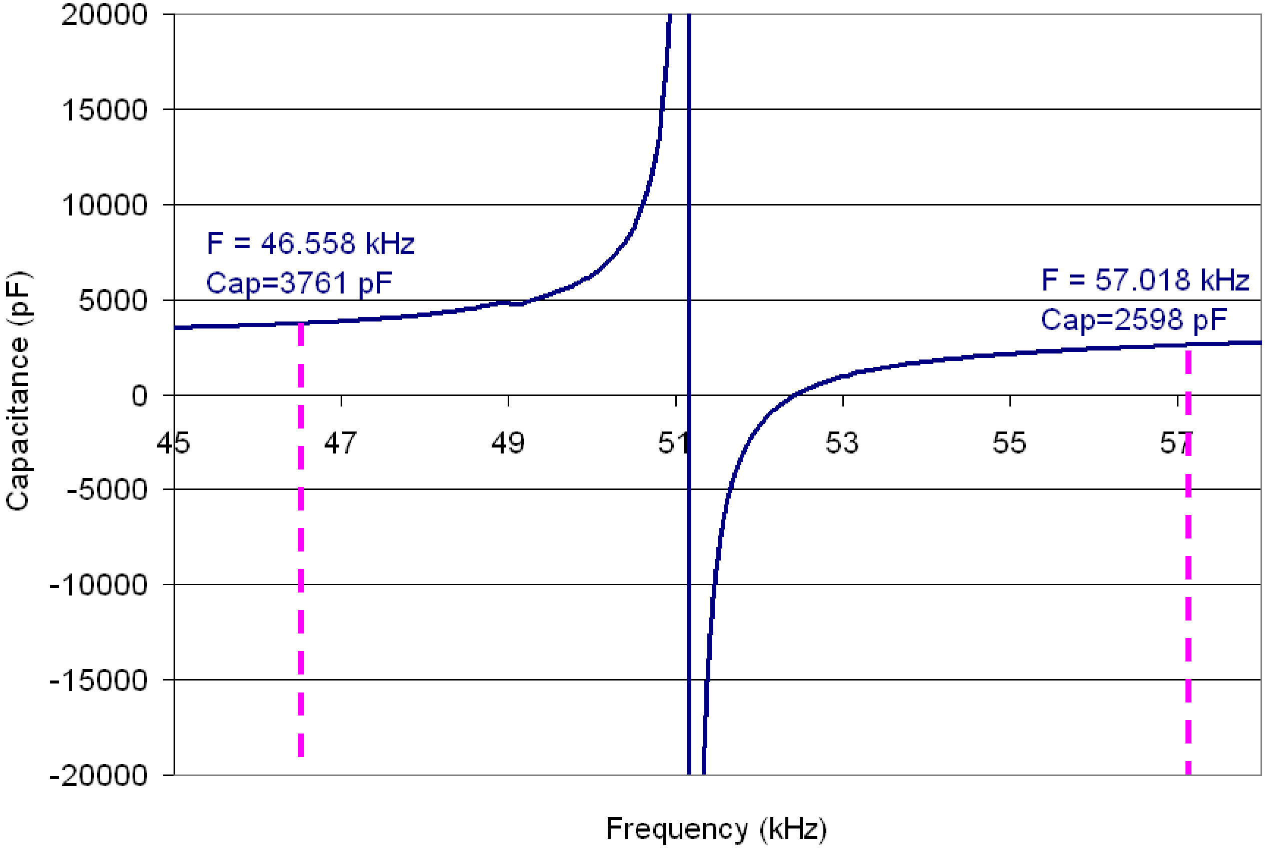
Mole Illustrative Example

Measured data



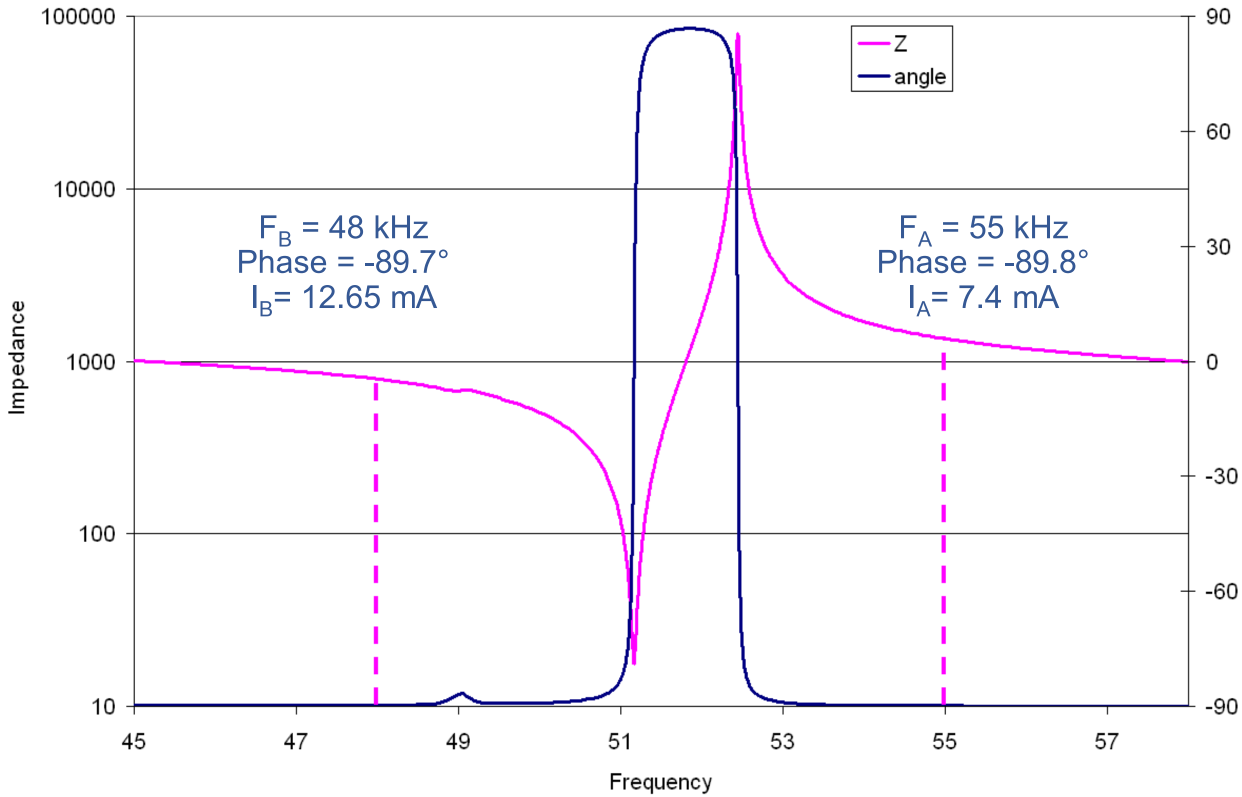
$$k = \sqrt{\frac{C_A - C_B}{\alpha(C_A + C_B)}}$$

$\alpha = 5$

$k = 0.191$

Evolving & Simplifying Mole

Premise: Factor M is proportional to coupling coefficient k



$$M = \sqrt{\frac{I_B - I_A}{I_B + I_A}}$$

$M = 0.512$

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Velocity Control Using Correction Factor M

M Proportional to K_{eff}

- Measuring/calculating Factor M
  - Measure current I_B and I_A at frequencies below and above resonance
    - Ensure current is substantially reactive (phase angle < -89°), widen frequency range if necessary
    - Calculate correction Factor M using the formula:

$$M = \sqrt{\frac{I_B - I_A}{I_B + I_A}}$$

- Calculating Factor M Scaling Factor
  - Computer model transducer with end effector attached
  - Simulate new and end-of-life conditions
    - Calculate Factor M for extreme conditions
    - Calculate current velocity ratio for extreme conditions
    - Calculate current correction factor based on Factor M

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Velocity Control Summary

- Method
  - Simple and efficient control
    - Eliminates the need to detect F_R and F_A involving multiple measurements
  - Based on measurement of current and phase below and above resonance
  - Can be applied during a prime cycle prior to operational use
  - Can also be applied during operational use
- Applications
  - Medical, industrial and Navy transducers control system algorithms based on constant current
  - Medical loose tip detection
    - Based on measurement of phase

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Practical Experiments

Simulation of Transducer Loads

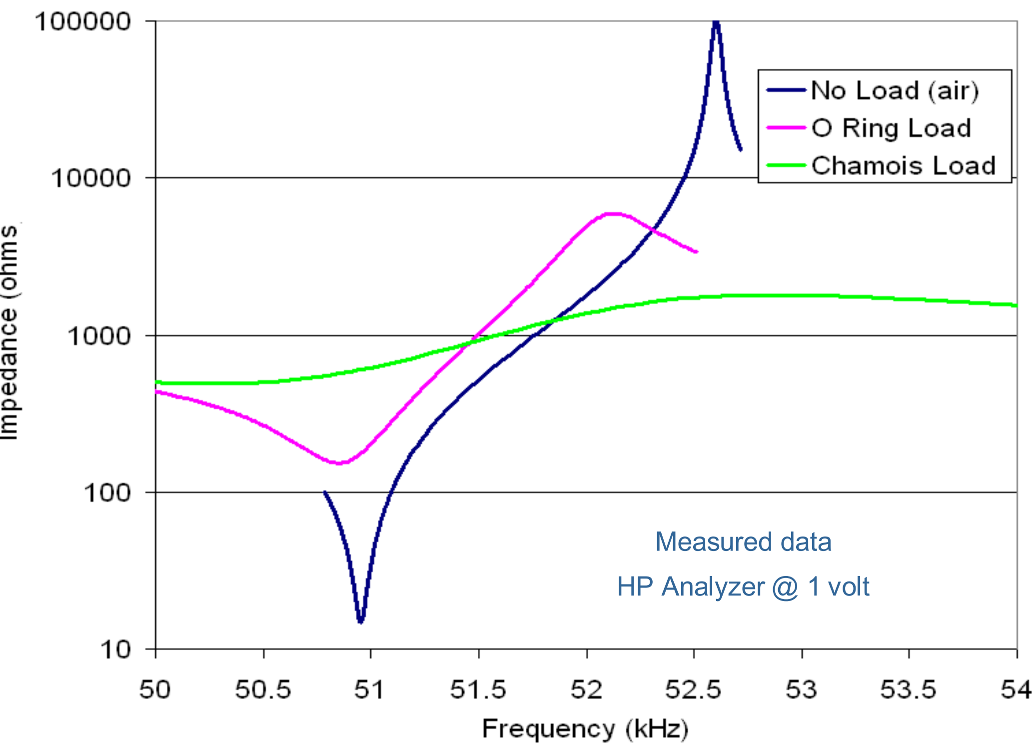
Air Q = 1000

O rings slid over horn Q=150

Typical Phaco and Dental Handpieces

Wet chamois wrapped over horn Q = 25

Typical Ultrasonic welding transducer



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Practical Experiments

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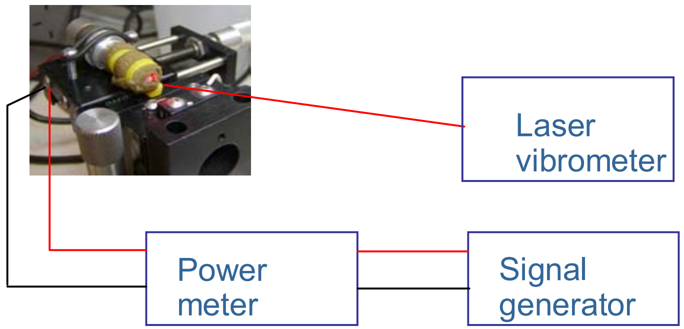

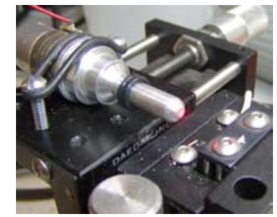

Transducer horn displacement 3 µm p-p

	F_R		F_A	
	V volts	I mA	V volts	I mA
No Load	1.3	57	54	.97
O Ring	9.0	53.3	45.7	11.3
Chamois	36	64	62	30

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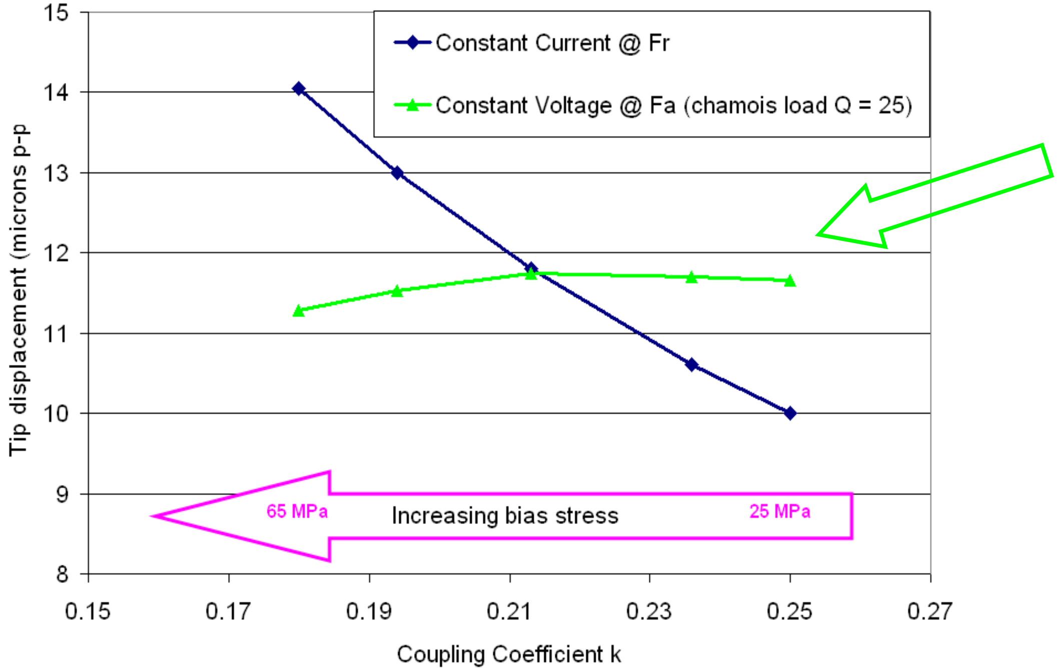
Computer Model

Effect of changes in piezo properties @ F_A and F_R

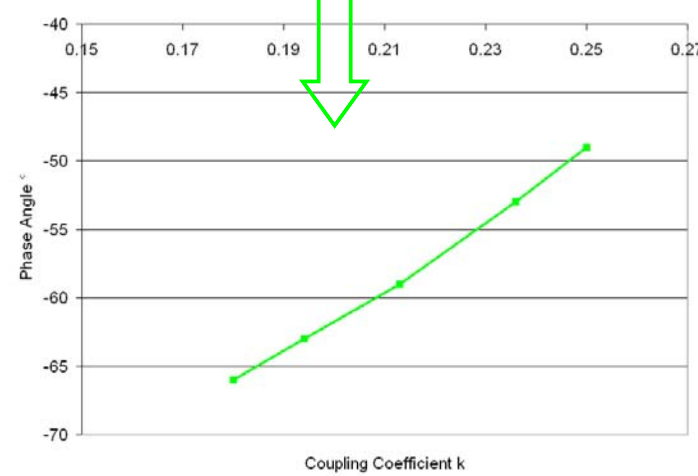


F_A Constant Voltage Drive

Relatively stable voltage/velocity ratio immune from changes in coupling coefficient

Piezo k_{33}

Selecting a Piezo material with high k_{33} is important because load is less reactive



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Optimizing System Performance

- Constant Current Operation at or Close to F_R
  - Lowest possible drive voltage (low tan δ loss and high efficiency)
  - Linear velocity control over a wide range of loading conditions
    - Q factors typically range from 100 to 2000
  - Requires a correction factor to compensate for changes associated with age, temperature and bias stress
- Constant Voltage Operation at or Close to F_A
  - Operating at very high power with low Q loads <100
    - Linear velocity control relatively immune from changes in piezo properties caused by heat
  - Low quiescent power in the “no-load” condition
    - Very high impedance at F_A

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- Piezo Innovations
  - This research has been internally funded by PI and is protected by a patent application.
- References

US Patents 3,432,691 Oscillatory Circuits for Electro-acoustic Converter & 3,443,130 Apparatus for Limiting the Motional Amplitude of an Ultrasonic Transducer (1969) Inventor Andrew Shoh

Ultrasonic Transducer Materials edited by Oskar E. Mattiat (Don Berlincourt referenced contributor). Published by Plenum Press 1971

Underwater Electroacoustic Transducers by D. Stansfield published by Peninsula Publishing

M. J. Earwicker, Mathematical Modelling of Piezoelectric Transducers, and Sean Winterer for developing the PiezoTran software based on this model

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