Piezoelectrics as Multifunctional Electromechanical Materials for Space Applications

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Acknowledgement

The NDEAA Lab team consisting of:

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- Dr. Xiaoqi Bao
- Dr. Zensheu Chang
- Dr. Mike Lih

Outline

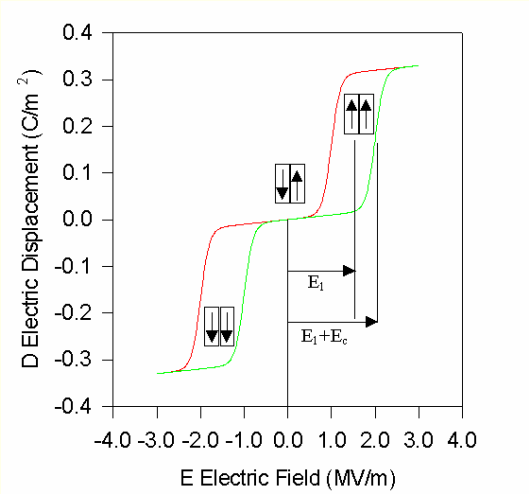
- Review a variety of Electroactive Material Dielectric and Strain Response
- Review the Macroscopic description of Piezoelectricity and look a the limitations. (Nonlinear, Dispersion, Loss)
- Present the various groups of piezoelectric materials (Ceramic, Single Crystal, Polymer) and typical size of effects
- Present the techniques used by transducer designers to amplify the limited strain (Cantilevers, Resonance, Stacking)
- Present the sensor examples (Quartz Crystal Microbalance QCM, Surface Acoustic Wave SAW Devices)
- Describe the various actuation and sensing mechanisms under development in the NDEAA Lab at JPL

Electroactive Response

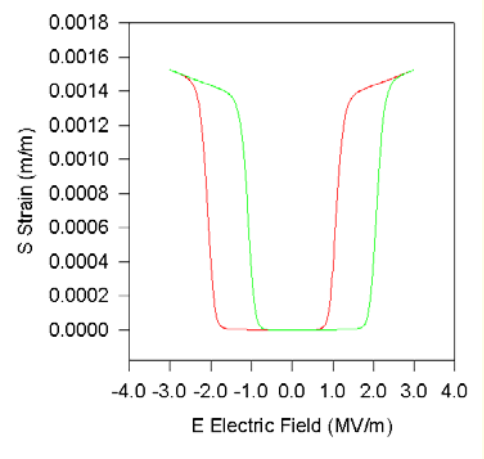
Anti-Ferroelectricity

- Low fields - counteracting domains stable
- Polarization curve opens up at large external electric field as domains switch

D vs E



S vs E

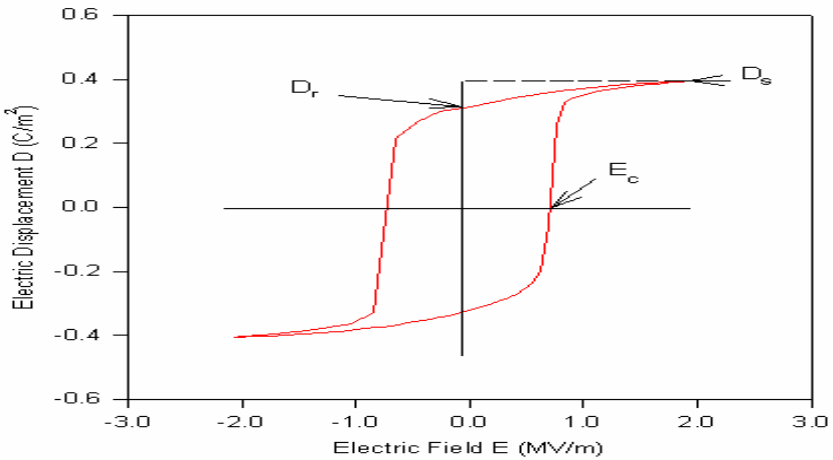


Electroactive Response

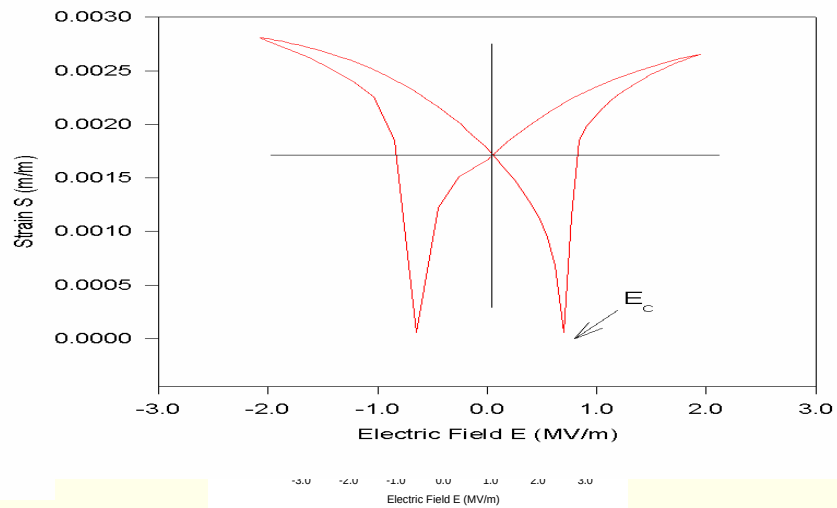
Ferroelectricity

- Presence of a spontaneous polarization
- Polarization can be switched by an external electric field.

D vs E



S vs E



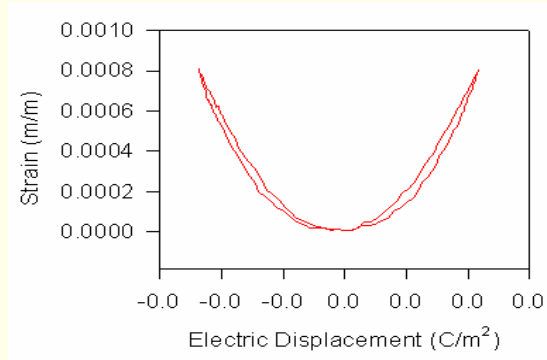
Common applications include ferroelectric RAM, electro-optic devices and displays

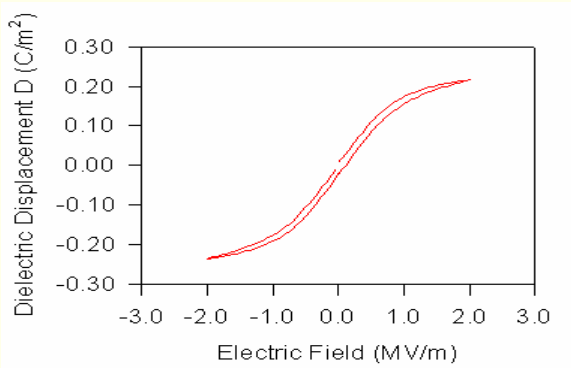
Electroactive Response

Electrostriction

Electrostriction is the name given to the quadratic relationship between the strain S and the electric displacement D present in most materials. The most fundamental form of this relationship is

$$S_{ij} = Q_{ijk} D_j D_k \longrightarrow$$

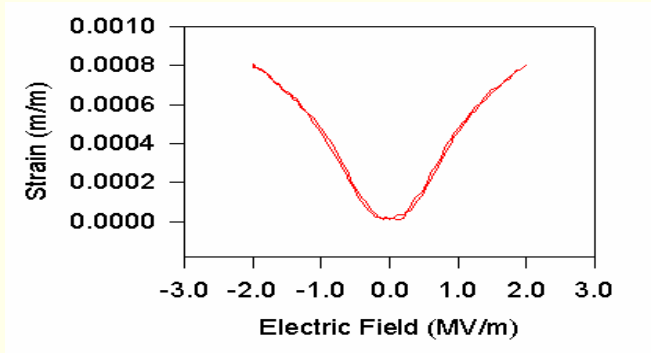




$$\longleftarrow$$

$$D_i = \varepsilon_{ij} E_j + \varepsilon_{ijkl} E_j E_k E_l + \varepsilon_{ijklmn} E_j E_k E_l E_m E_n + \ldots\ldots$$

$$S_{ij} \approx \lambda_{ijk} E_k^2 \longrightarrow$$



Applications

Actuators, sonar projectors, ultrasonic transducers

Semi Empirical Modeling (Ising Spin model)
Start with antiferroelectric

$$D := \left[\frac{Ds}{2} \cdot \tanh[k \cdot (E + E1 \cdot R2 - Ec \cdot R1)] + \frac{Ds}{2} \cdot \tanh[k \cdot (E - E1 \cdot R2 - Ec \cdot R1)] + \varepsilon \cdot E \right]$$

D is electric displacement

E is field

Ds is the Saturation Electric Displacement

±(E1 – Ec) is the field at which the anti ferroelectric becomes stable

±(E1 + Ec) is the field at which the domains switch to parallel orientation.

k is saturation coefficient (k large switching occurs abruptly k = μ/KT)

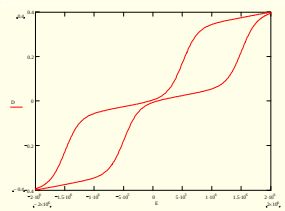
$R1 = \frac{dE/dt}{|dE/dt|}$ normalized first time derivative of the electric field

$R2 = \frac{d^2E/dt^2}{|d^2E/dt^2|}$ normalized second derivative of the electric field wrt time

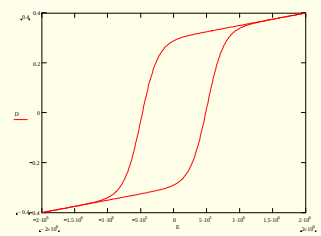
ε is a term to account for linear saturation

$$D := \left[\frac{Ds}{2} \cdot \tanh[k \cdot (E + E1 \cdot R2 - Ec \cdot R1)] + \frac{Ds}{2} \cdot \tanh[k \cdot (E - E1 \cdot R2 - Ec \cdot R1)] + \varepsilon \cdot E \right]$$

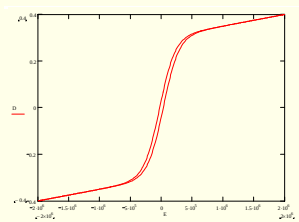
All constants Antiferroelectric



E1 = 0 Ferroelectric



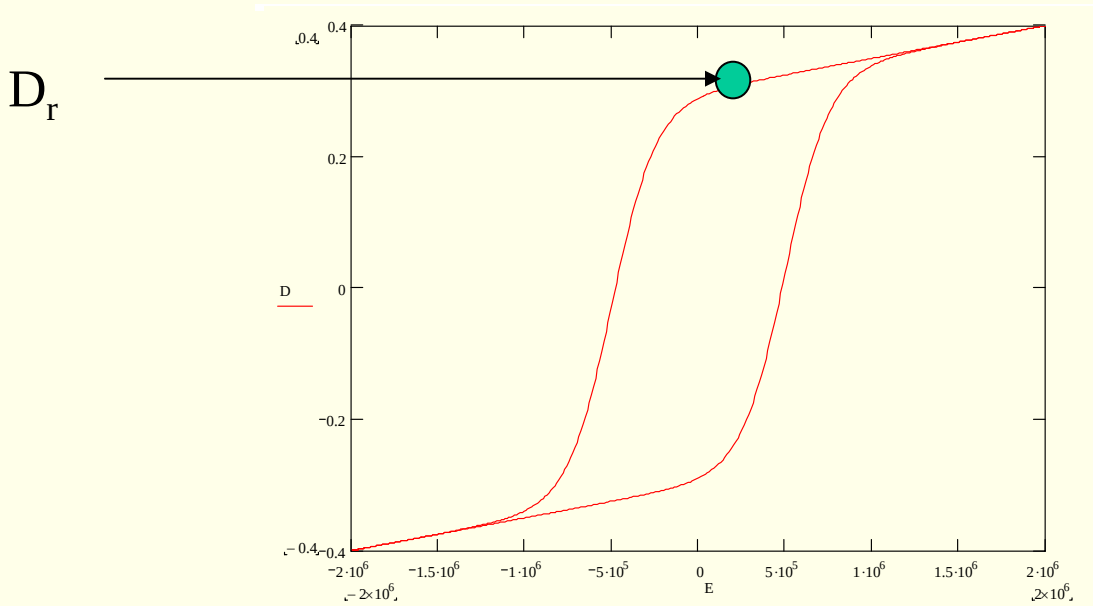
Ec small Electrostrictive



For all the above $S = QD^2$

What about piezoelectrics?

Piezoelectric coefficient in the poled materials is due to coupling of the electrostrictive coefficient with the remenant electric displacement.



$$S = Q(D + Dr)^2$$
$$= (2QDr)D + QD^2 + QDr^2$$
$$= gD + \text{nonlinear term} + \text{remanent strain}$$

Piezoelectricity

Coupled "Linear" Relationship between the strain S, electric displacement D and the electric field E and the stress T

$$S_p = s^E_{pq} T_q + d_{pm} E_m$$

$$D_m = \varepsilon^T_{mn} E_n + d_{pm} T_p$$

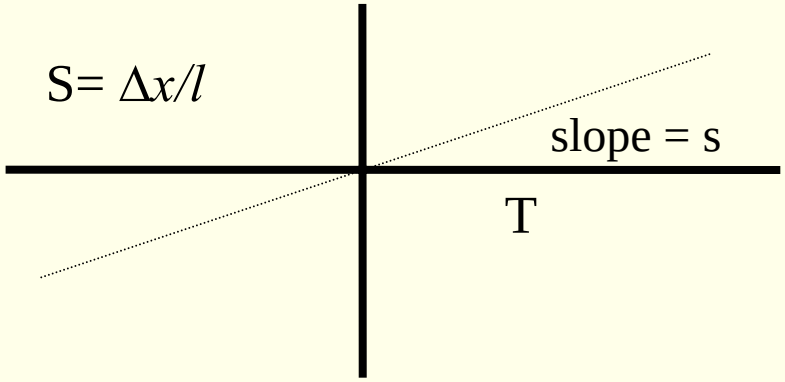
Derived from thermodynamic potentials

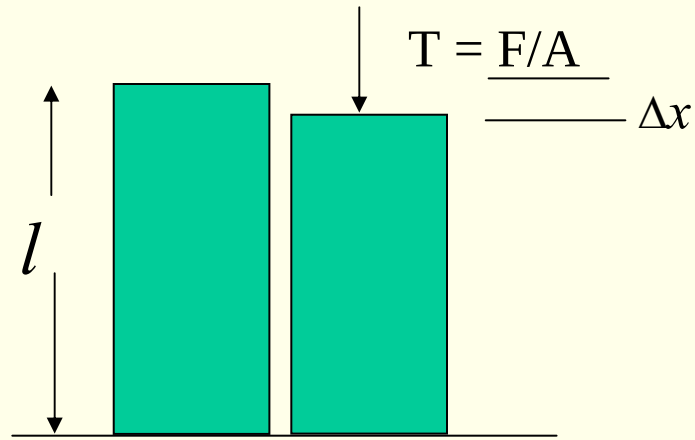
•Superscripts designate boundary conditions
•Subscripts designate anisotropy

•Notation: IEEE Standards on Piezoelectricity

Elastic Response – Strain S, Stress T

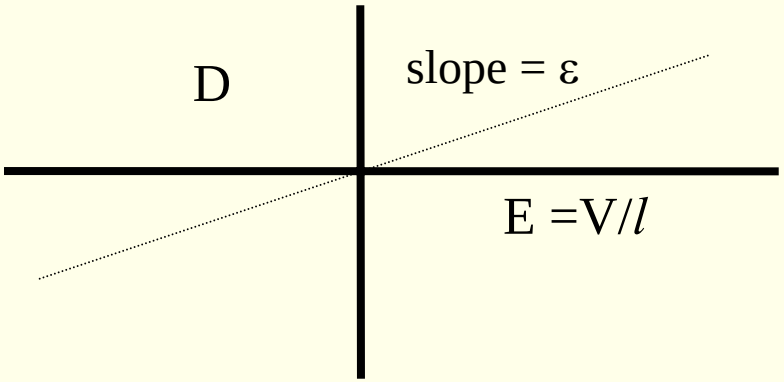
$S = sT$ s is compliance

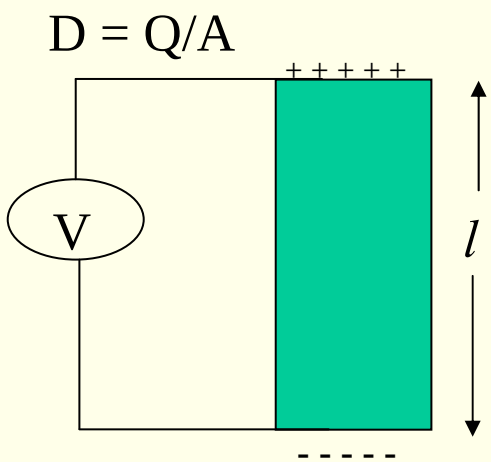




Dielectric Response – Field E, Electric Displacement D

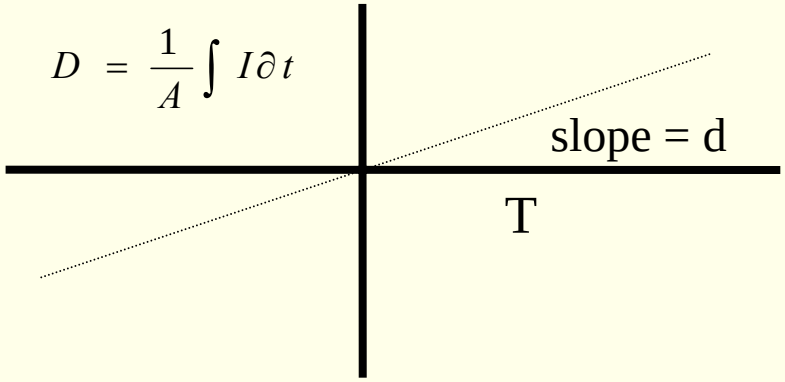
$\mathbf{D} = \varepsilon_0\mathbf{E}+\mathbf{P} = \varepsilon\mathbf{E}$ ε is permittivity

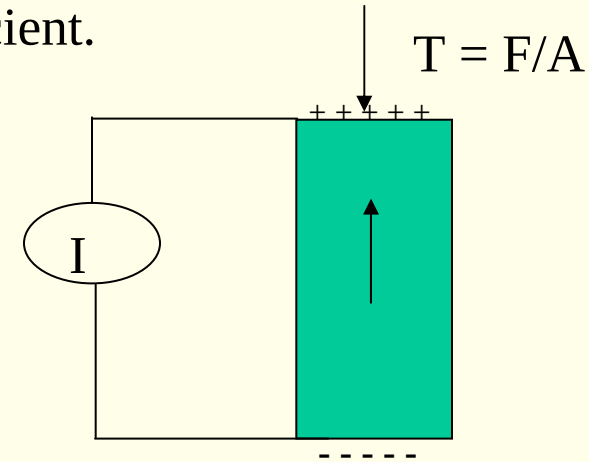




Direct Piezoelectric Response – Electric Displacement D, Stress T

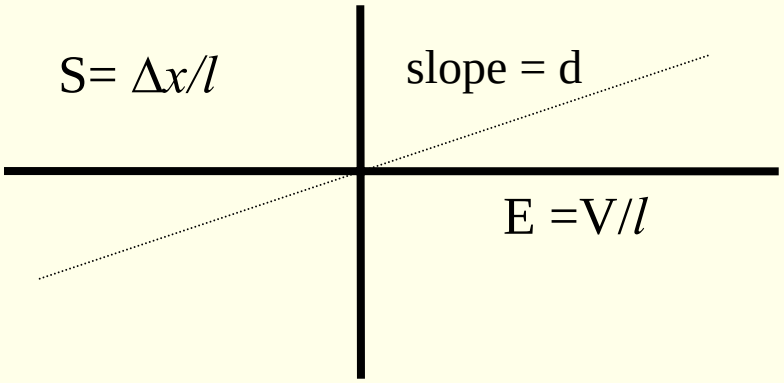
D = dT d is piezoelectric charge coefficient.

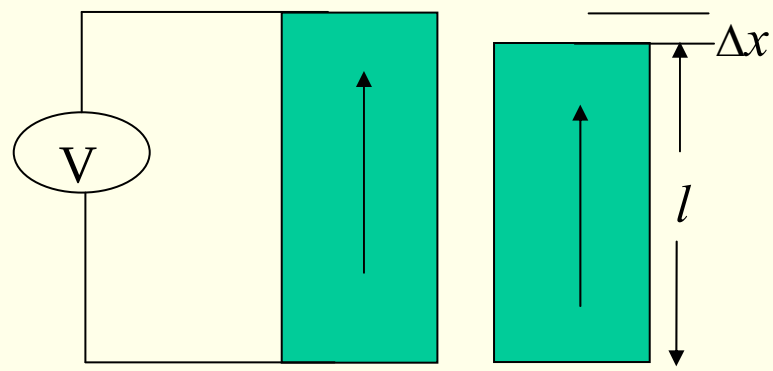




Converse Piezoelectric Response – Field E, Strain S

S = dE d is piezoelectric charge coeff.

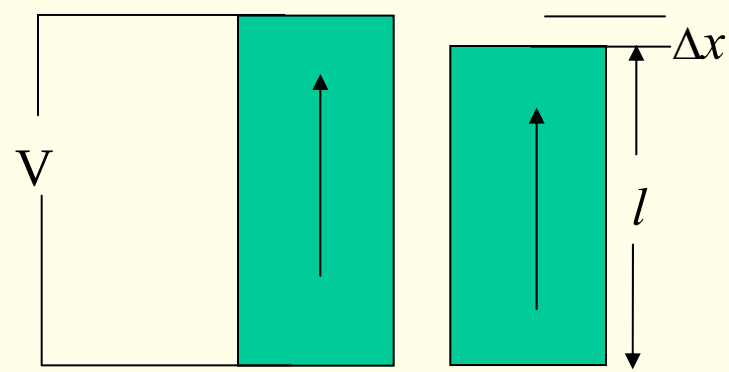




Coupling constant

$$k^2 = \frac{\text{Output Mechanial Energy Density}}{\text{Input Electrical Energy Density}} = \frac{sT^2}{\varepsilon E^2} \text{ or vice versa}$$

$$k^2 \propto \frac{d^2}{\varepsilon s}$$



Energy conversion per cycle

Thermodynamic Derivation

Sample under isothermal and adiabatic conditions and ignoring higher order effects the elastic Gibbs function may be described by

$$G_1 = -\tfrac{1}{2}\left(s^D_{ijkl}T_{ij}T_{kl} + 2g_{nij}D_nT_{ij}\right) + \tfrac{1}{2}\beta^T_{mn}D_mD_n$$

The linear equations of piezoelectricity for this potential are determined from the derivative of G_1 and are

$$S_{ij} = -\frac{\partial G_1}{\partial T_{ij}} = s^D_{ijkl}T_{kl} + g_{nij}D_n$$

$$E_m = \frac{\partial G_1}{\partial D_m} = \beta^T_{mn}D_n - g_{nij}T_{ij}$$

Other Forms of Linear Piezoelectricity

$$S_p = s^D_{pq} T_q + g_{pm} D_m$$
$$E_m = \beta^T_{mn} D_m - g_{pm} T_p$$

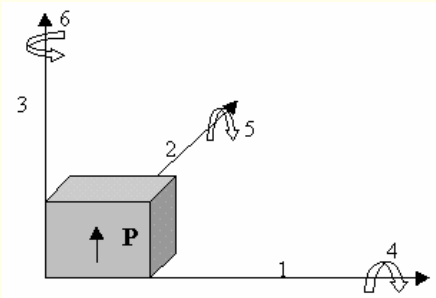
$$S_p = s^E_{pq} T_q + d_{pm} E_m$$
$$D_m = \varepsilon^T_{mn} E_n + d_{pm} T_p$$

$$T_p = c^E_{pq} S_q - e_{pm} E_m$$
$$D_m = \varepsilon^S_{mn} E_n + e_{pm} S_p$$

$$T_p = c^D_{pq} S_q - h_{pm} D_m$$
$$E_m = \beta^S_{mn} D_n - h_{pm} S_p$$

Reduced Matrix Form

$$\left|\frac{S}{D}\right| = \left|\begin{matrix} \left|s^{E}(6 \times 6)\right| & \left|d^{T}(6 \times 3)\right| \\ \left|d(3 \times 6)\right| & \left|\varepsilon^{T}(3 \times 3)\right| \end{matrix}\right| \bullet \left|\frac{T}{E}\right|$$



$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \left[\begin{array}{cccccc|ccc} s^E_{11} & s^E_{12} & s^E_{13} & s^E_{14} & s^E_{15} & s^E_{16} & d_{11} & d_{12} & d_{13} \\ s^E_{21} & s^E_{22} & s^E_{23} & s^E_{24} & s^E_{25} & s^E_{26} & d_{21} & d_{22} & d_{23} \\ s^E_{31} & s^E_{32} & s^E_{33} & s^E_{34} & s^E_{35} & s^E_{36} & d_{31} & d_{32} & d_{33} \\ s^E_{41} & s^E_{42} & s^E_{43} & s^E_{44} & s^E_{45} & s^E_{46} & d_{41} & d_{42} & d_{43} \\ s^E_{51} & s^E_{52} & s^E_{53} & s^E_{54} & s^E_{55} & s^E_{56} & d_{51} & d_{52} & d_{53} \\ s^E_{61} & s^E_{62} & s^E_{63} & s^E_{64} & s^E_{65} & s^E_{66} & d_{61} & d_{62} & d_{63} \\ \hline d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} & \varepsilon^T_{11} & \varepsilon^T_{12} & \varepsilon^T_{13} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} & \varepsilon^T_{21} & \varepsilon^T_{22} & \varepsilon^T_{23} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} & \varepsilon^T_{31} & \varepsilon^T_{32} & \varepsilon^T_{33} \end{array}\right] \bullet \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

PZT has C_∞ symmetry.
Therefore in ideal case only 10 independent constants are required to describe the response.

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 & 0 & 0 & d_{13} \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 & 0 & 0 & d_{13} \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 & 0 & 0 & d_{33} \\ 0 & 0 & 0 & s_{55}^E & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 & d_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}^E - s_{12}^E) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{15} & 0 & \varepsilon_{11}^T & 0 & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 & 0 & \varepsilon_{11}^T & 0 \\ d_{13} & d_{13} & d_{33} & 0 & 0 & 0 & 0 & 0 & \varepsilon_{33}^T \end{bmatrix} \bullet \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Real or Actual Piezoelectrics

$$\varepsilon_{mn}^{T} = \varepsilon_{mnr}^{T}\left(\omega, E_i, T_{ij}, T, t\right) + i\varepsilon_{mni}^{T}\left(\omega, E_i, T_{ij}, T, t\right)$$

$$d_{mn} = d_{mnr}\left(\omega, E_i, T_{ij}, T, t\right) + id_{mni}\left(\omega, E_i, T_{ij}, T, t\right)$$

$$s_{mn}^{E} = s_{mnr}^{E}\left(\omega, E_i, T_{ij}, T, t\right) + is_{mni}^{E}\left(\omega, E_i, T_{ij}, T, t\right)$$

Loss

Dispersion

Non-Linearities

Temperature Dependence

Aging

ALL May be Significant

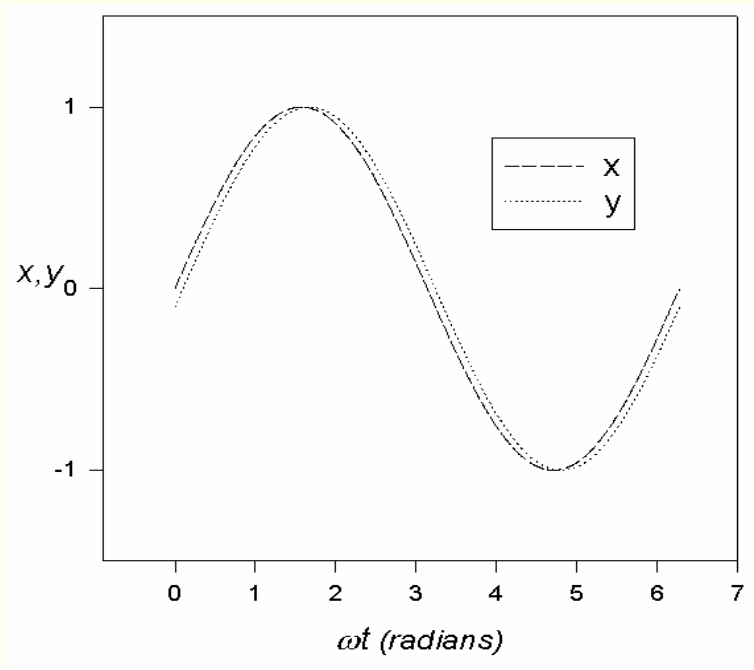
Linear Loss

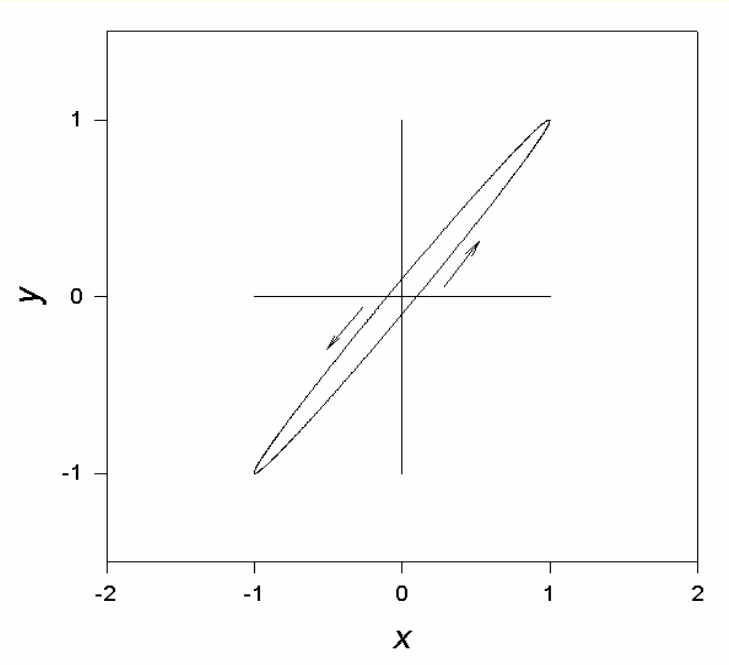
y = bx

where x and y can be the field E, Displacement D, stress T or strain S

$$x = x_0 \sin(\omega_0 t) \qquad y = |b|\, x_0 \left[\sin(\omega_0 t + \delta)\right]$$

- b real then y and x are in phase.
- b complex then y and x are out of phase and depending on the variables a energy loss is present .



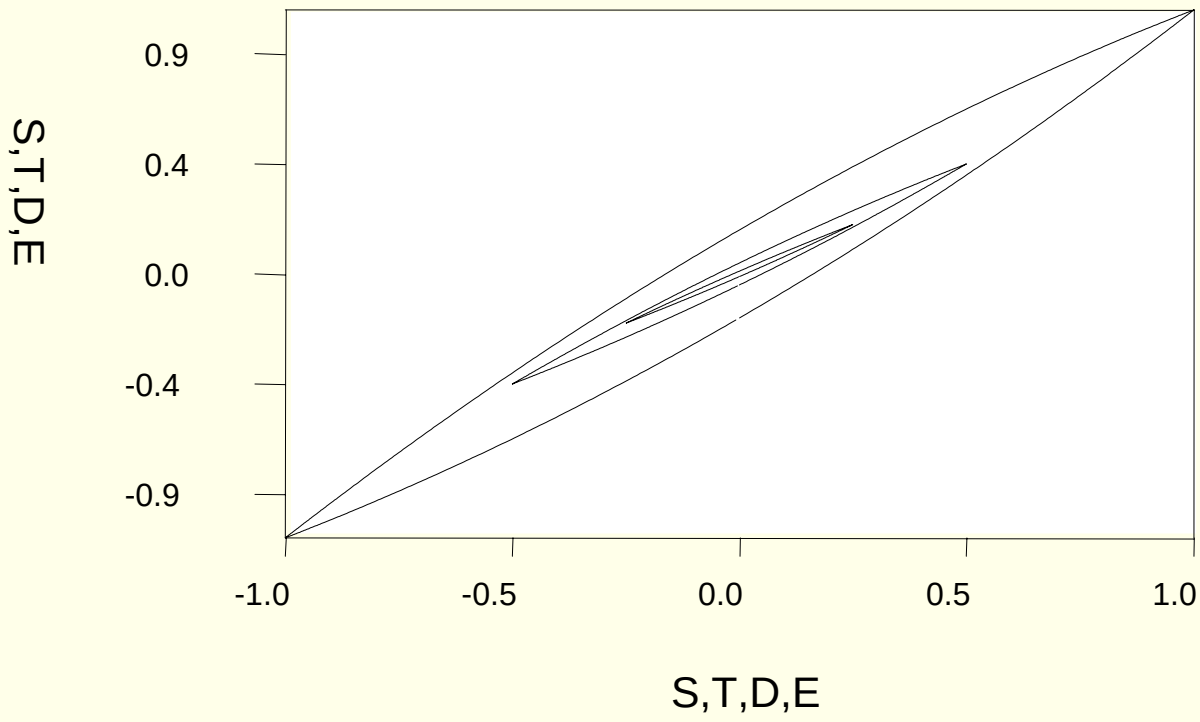


- *Material Loss* - First order correction

- Rayleigh's law $Y = (a_0 + \alpha X_m)X \pm \alpha/2(X_m^2 - X^2)$

where the response increases linearly with maximum field/stress and the remanence increases with the square of the field/stress

Rayleigh Behavior (1st order)

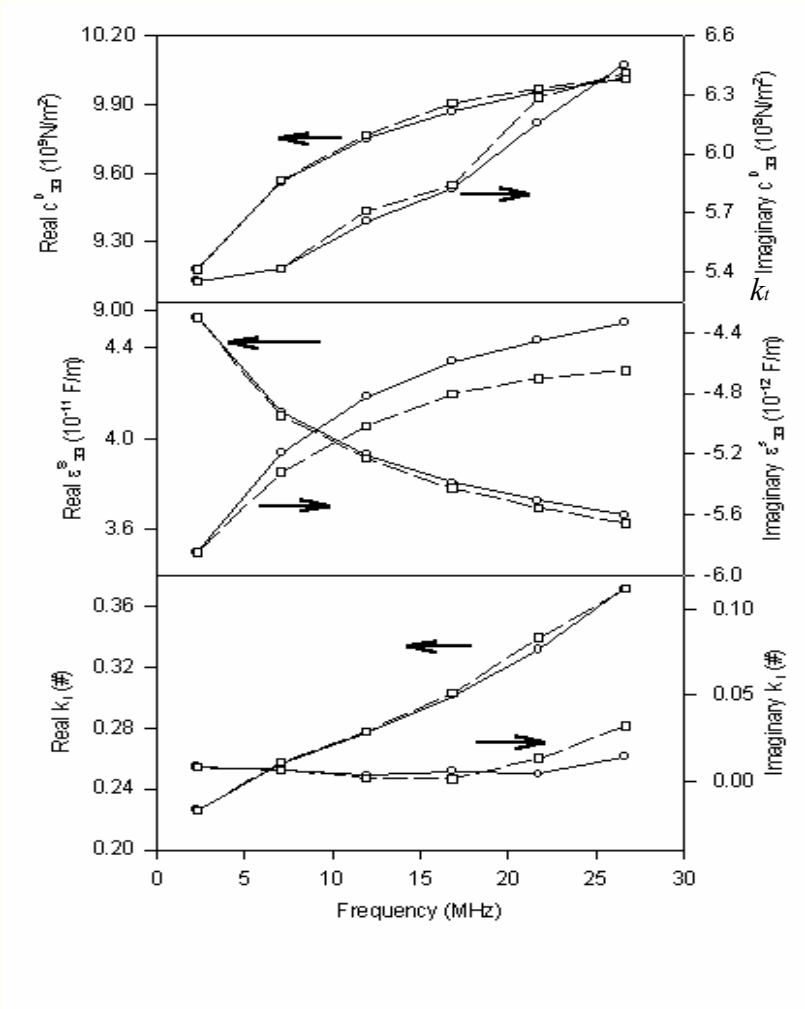


Dispersion

Causal (response follows input)

•Passivity (Can only dissipate)

Example PVDF-TRFE



$$\varepsilon_{33}^{S} = \varepsilon_{33}^{S}(\omega)' + i\varepsilon_{33}^{S}(\omega)''$$

$$c_{33}^{D} = c_{33}^{D}(\omega)' + ic_{33}^{D}(\omega)''$$

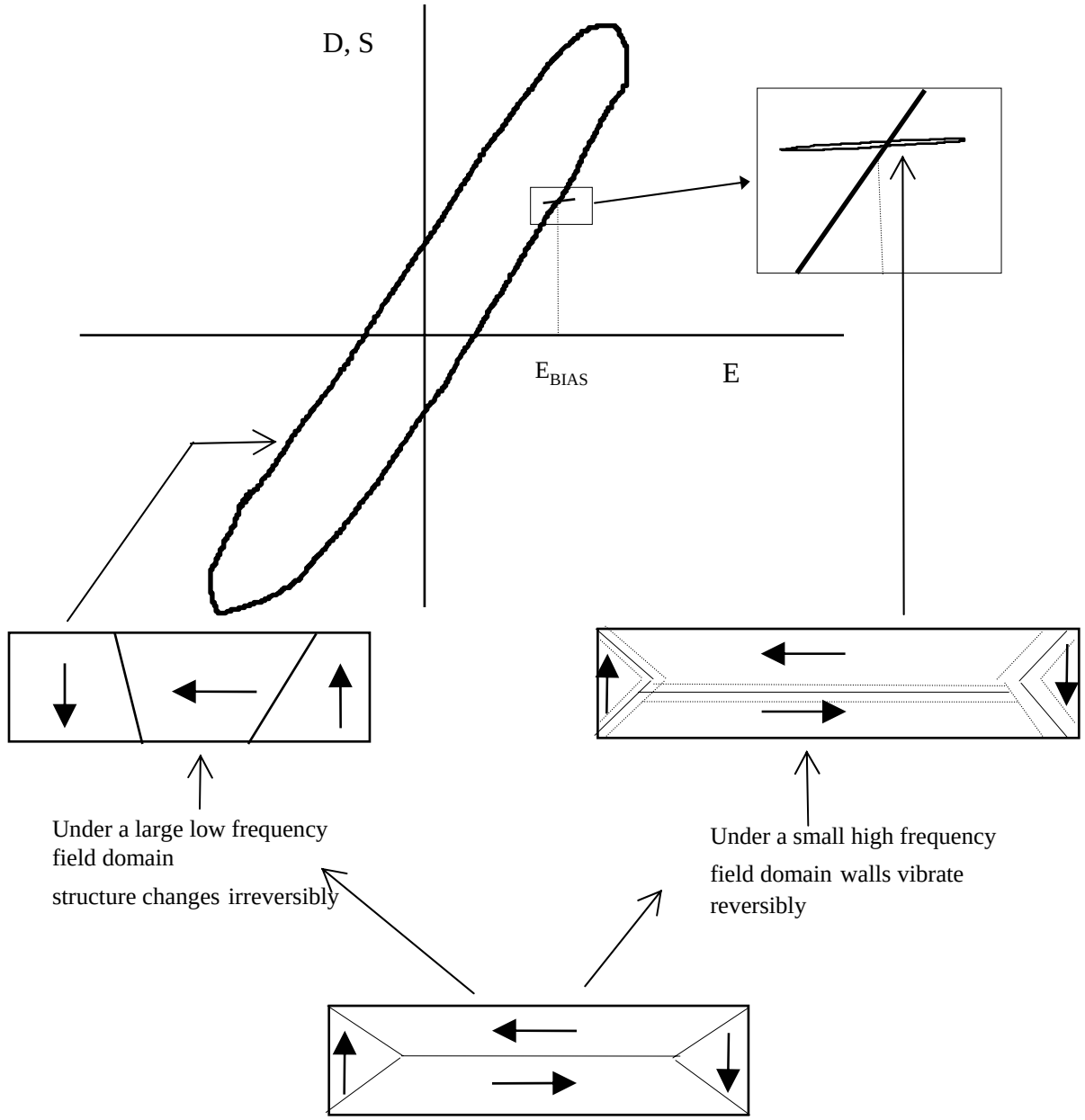
$$k_t = k_t(\omega)' + ik_t(\omega)''$$

Non Linearities

- First order corrections – Rayleigh
- Higher order expand the elastic Gibbs energy in field and stress

- Definition of how material constants are measured

1. Average response ($\Delta Y/\Delta X$)
2. Differential response (dY/dX)
3. Biased small signal differential response($\partial Y/\partial X$ at X_0)


D, S
E_{BIAS}
E
Under a large low frequency field domain
structure changes irreversibly
Under a small high frequency field domain walls vibrate reversibly

Piezoelectric Properties - Ceramics

TABLE 5.2-1: Piezoelectric coefficients and permittivity at three temperatures for three typical commercial PZT materials [Based on: Hooker, 1998].
Performance Standard set out by Navy eg, Navy I , Navy II, etc

Property	PZT 4			PZT 5A			PZT 5H*		
	-150°C	25°C	250°C	-150°C	25°C	250°C	-150°C	25°C	180°C
d_{33} (pC/N)	210	225	360	190	350	440	260	585	900
d_{31} (pC/N)	-70	-85	-130	-100	-190	-270	-115	-265	-500
ε (10^{-9} F/m)	7.1	9.7	27	5.3	10	27	7.5	28	124
*maximum in dielectric constant is at 180°C									

Piezoelectric Properties - Polymers

PVDF

d_{31} = 28 pC/N, d_{32} =4 pC/N, d_{33} =-35 pC/N

Relative Permittivity =10-15
Mechanical Q = 10
Coupling up to 0.15

PVDF/TrFE 75/25 Copolymer

d_{31} = 10.7 pC/N, d_{32} =10.1 pC/N, d_{33} =-33.5 pC/N

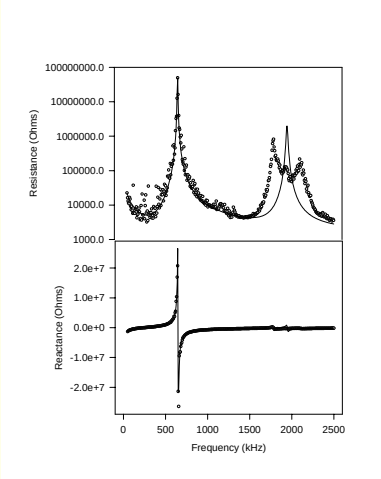
Relative Permittivity =5-10
Mechanical Q = 10
Coupling up to 0.25

Piezoelectric Properties – Single Crystals

Le mode PZN-PT 8%

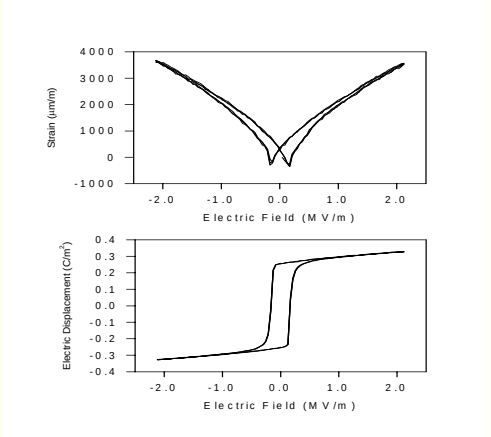
Table 2: The material constant for the length extensional resonance mode, at room temperature, sample 2.

Material constant		
s^D_{33} (m^2/V)	Re $\times 10^{-11}$	1.73
	Im $\times 10^{-13}$	-1.76
s^E_{33} (m^2/V)	Re $\times 10^{-10}$	1.30
	Im $\times 10^{-12}$	-2.17
d_{33} (C/N)	Re $\times 10^{-9}$	1.97
	Im $\times 10^{-11}$	-3.32
ε^T_{33} (F/m)	Re $\times 10^{-8}$	3.42
	Im $\times 10^{-10}$	-5.48
k_{33}	Re	0.93
	Im x 10^{-4}	-5.06

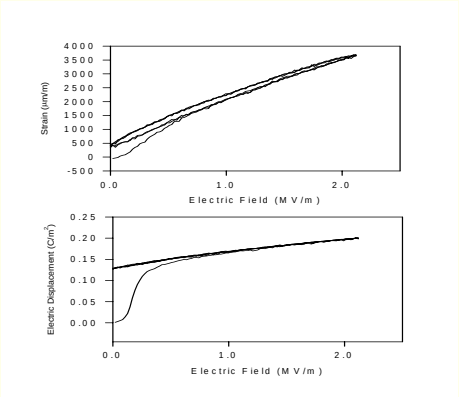


High field studies PZN-PT 4.5%

Bipolar Excitation



Unipolar Excitation



Piezoelectric Properties – Single Crystals

AT Cut Quartz

$\boldsymbol{\varepsilon}^{S}$	$5.46\text{x}10^{-11}(1 - 0.024i)$
$\mathbf{c}^{D}$	$2.96\text{x}10^{10}(1 + 0.00012i)$
$\boldsymbol{k}$	$0.072(1 - 0.0088i)$
$\boldsymbol{h}$	$1.67\text{x}10^{9}(1 + 0.021\ i)$

Density = 2650 kg/m^3

Q's up to 100,000
10^6 in vacuum

Temperature stability extremely high about RT
Which is the reason they are used timing

Limitation of Piezoelectrics

Consider Motorola 3203 HD PZT
which has a fairly large d_{33} constant

$S = d_{33}E$

$d_{33} = 6x10^{-10}$ m/V

For $E = 10^5$ V/m

$T = e_{33}E$

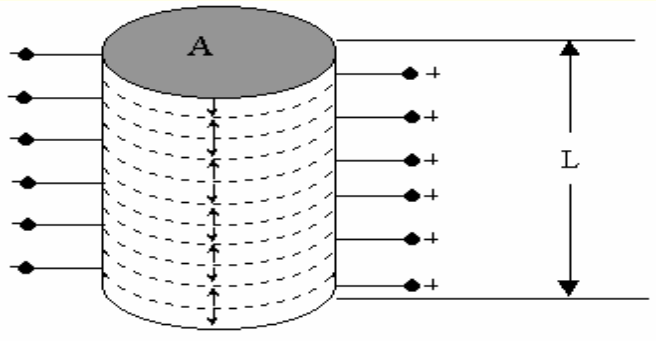
$e_{33} = 25$ C/m^2

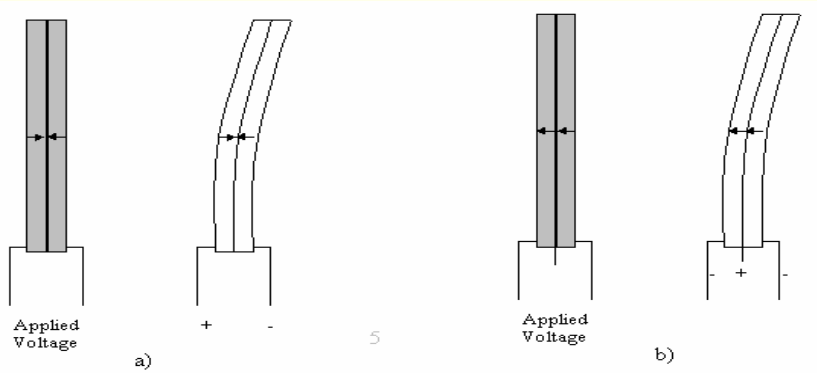
$T = 2.5$ MPa

$S = 6x10^{-5}$

Q. What do you do now?
A. Design around this. → Resonators or other Strain Amplification techniques

Stacks and Bimorphs

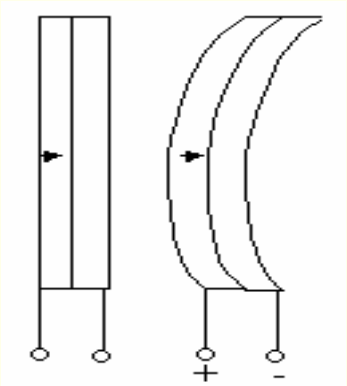




$$d_{33}^{eff} = nd_{33} \qquad C = \frac{n^2 \varepsilon_{33}^{T} A}{L}$$

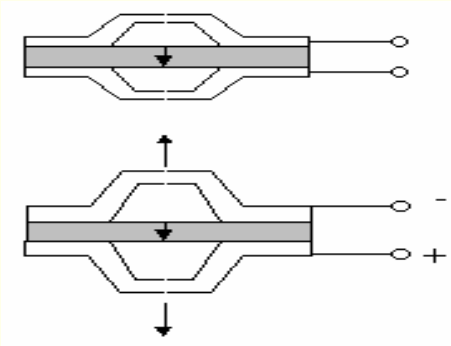
$$\Delta y = \frac{3d_{31}VL^2}{2t^2} \qquad \Delta y = \frac{3d_{31}VL^2}{t^2}$$

Uni-morphs

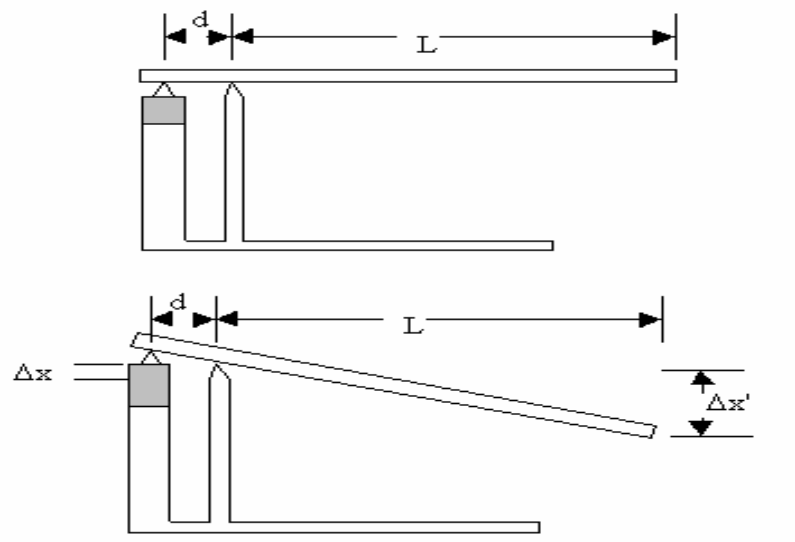


Example – Clemson's RAINBOW
- NASA's THUNDER

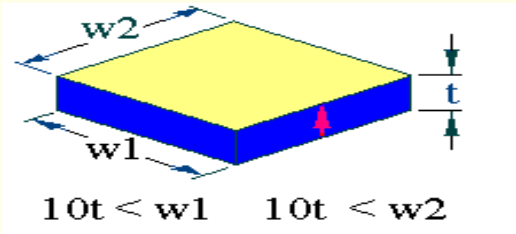
Flextensional Devices



Cantilevers



Resonator Example Thickness Extensional



Linear Equations
Of Piezoelectricity

$$\mathbf{T}_3 = \mathbf{c}_{33}^{D}\mathbf{S}_3 - \mathbf{h}_{33}\mathbf{D}_3$$

$$\mathbf{E}_3 = -\mathbf{h}_{33}\mathbf{S}_3 + \beta_{33}^{s}\mathbf{D}_3$$

Wave Equation

$$\frac{\partial^2 u_3}{\partial t^2} = \frac{\mathbf{c}_{33}^{D}}{\rho}\frac{\partial^2 u_3}{\partial x_3^2}$$

B.C.

$$\mathbf{T}_3 = 0 \text{ at } x_3 = 0$$

$$T_3 = 0 \text{ at } x_3 = t$$

Also $S = du/dx$ and

$$\mathbf{v}_D = \sqrt{\frac{\mathbf{c}_{33}^{D}}{\rho}}$$

Strain from Wave Equation and Boundary Conditions

$$\mathbf{S_3} = \left[\frac{\mathbf{h_{33}D_3}}{\mathbf{c}_{33}^{D}} \left(\cos\left(\frac{\omega x_3}{\mathbf{v}_D}\right) - \frac{\cos\left(\frac{\omega t}{\mathbf{v}_D}\right) - 1}{\sin\left(\frac{\omega t}{\mathbf{v}_D}\right)} \sin\left(\frac{\omega x_3}{\mathbf{v}_D}\right) \right) \right]$$

Calculate Voltage

$$\mathbf{V} = -\int_0^t \mathbf{E}_3 dx_3 = \int_0^t \left(\mathbf{h}_{33}\mathbf{S}_3 - \boldsymbol{\varepsilon}_{33}^{s}\mathbf{D}_3\right) dx_3$$

$$\mathbf{V} = -\boldsymbol{\varepsilon}_{33}^{s}\mathbf{D}_3 l - \frac{\mathbf{h}_{33}^{2}\mathbf{D_3}\mathbf{v}_D}{\mathbf{c}_{33}^{D}\omega} \left(\frac{2\cos\left(\frac{\omega t}{\mathbf{v}_D}\right) - 2}{\sin\left(\frac{\omega t}{\mathbf{v}_D}\right)} \right)$$

Calculate Current

$$\mathbf{I} = A\frac{d\mathbf{D}_3}{dt} = -i\omega A\mathbf{D}_3$$

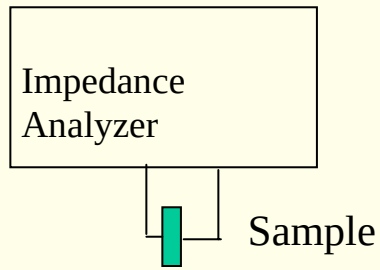
Finally Determine the complex Impedance

VERY IMPORTANT

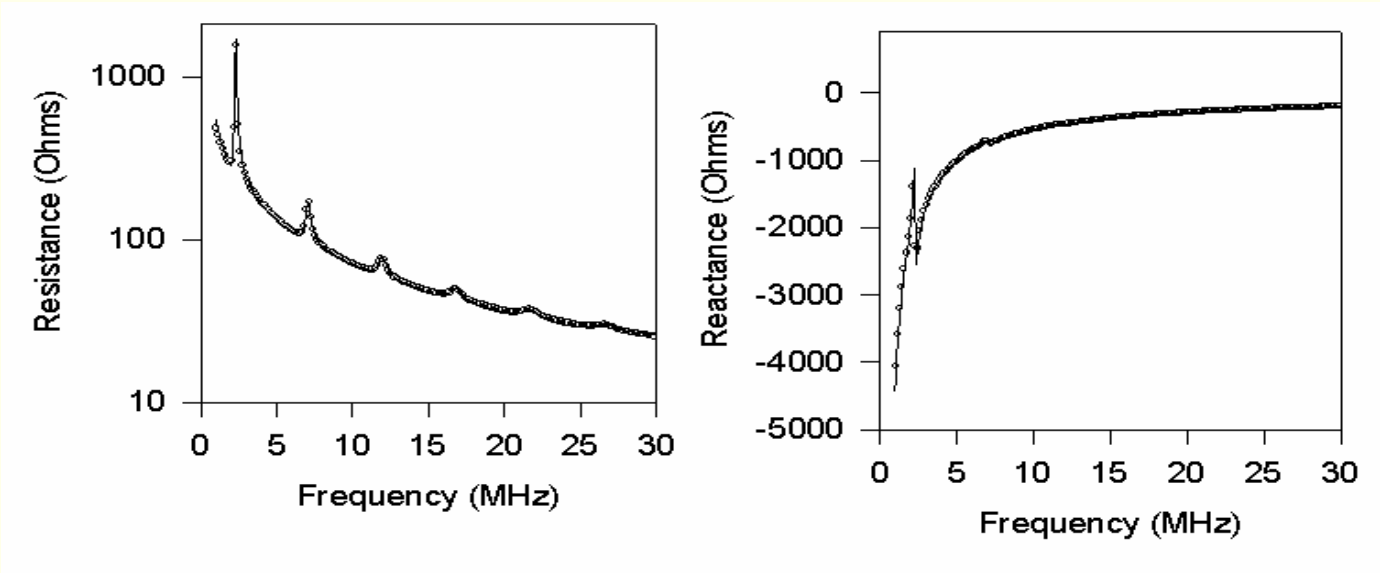
$$\mathbf{Z} = \frac{\boldsymbol{\varepsilon}_{33}^{s} t + \frac{\mathbf{h}_{33}^{2}\mathbf{v}_D}{\mathbf{c}_{33}^{D}\omega}\left(2\tan\left(\frac{\omega t}{2\mathbf{v}_D}\right)\right)}{i\omega A}$$

$$\mathbf{k}_t^2 = \frac{\mathbf{h}_{33}^2}{\beta_{33}^S \mathbf{c}_{33}^D} \qquad 4 f_p = \frac{2 \mathbf{v}_D}{l} \qquad \beta_{33}^S = \frac{1}{\varepsilon_{33}^S}$$

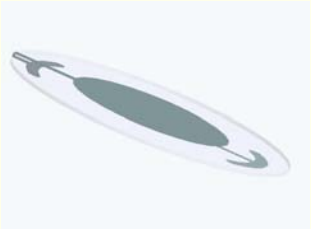
$$\mathbf{Z} = \frac{t}{i\omega A \varepsilon_{33}^S}\left(1 - \frac{\mathbf{k}_t^2 \tan\left(\frac{\omega}{4\mathbf{f_p}}\right)}{\frac{\omega}{4\mathbf{f_p}}}\right)$$



Simple Measurement Method to determine the Elastic Dielectric and Piezoelectric Constants and loss by measuring the complex impedance as a function of frequency

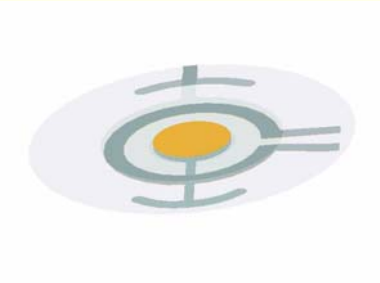


Common Modes of Sensing



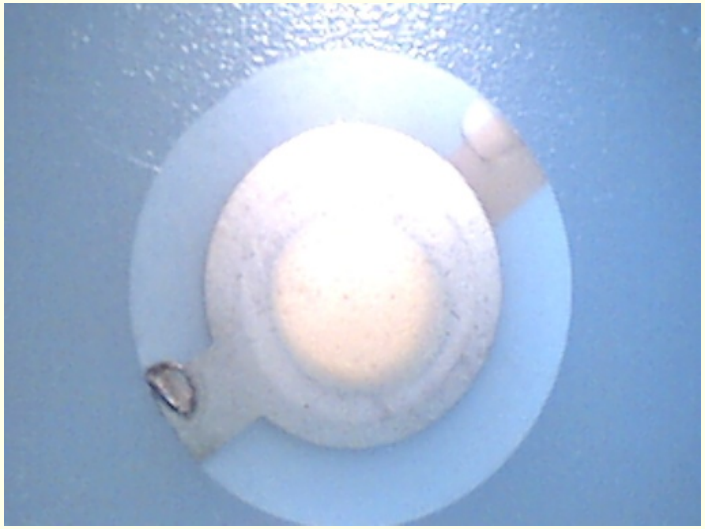
Select crystal properties, axis to monitor Δf due to specific environmental variable, Temperature, Pressure, Field, Viscosity or Mass change due to thermal or electrochemical deposition.

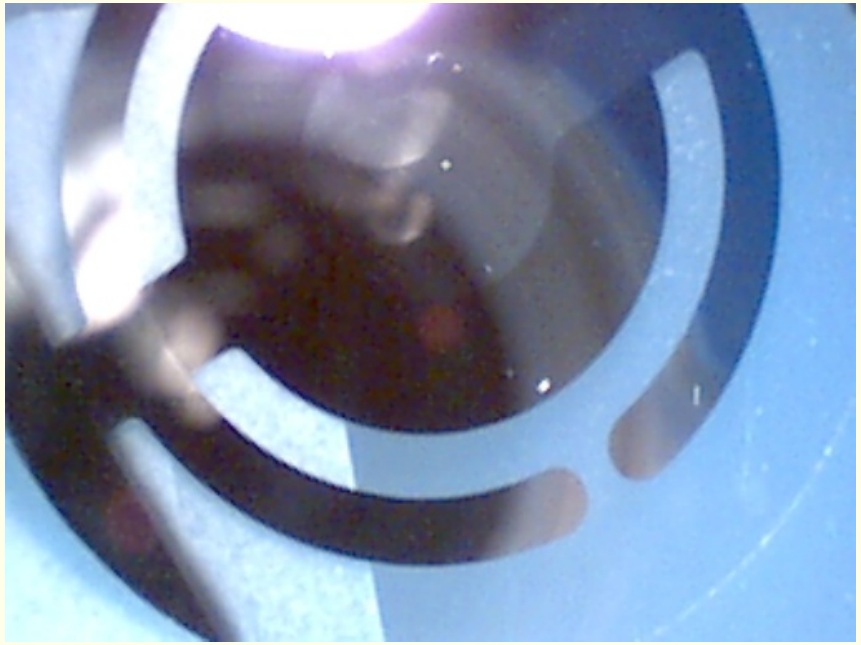
Select interface layer axis to monitor Δf due to specific reactant, adsorbent in enviroment



Integrate heater/cooler for thermal adsorption-desorption curves.

Quartz shear resonator examples

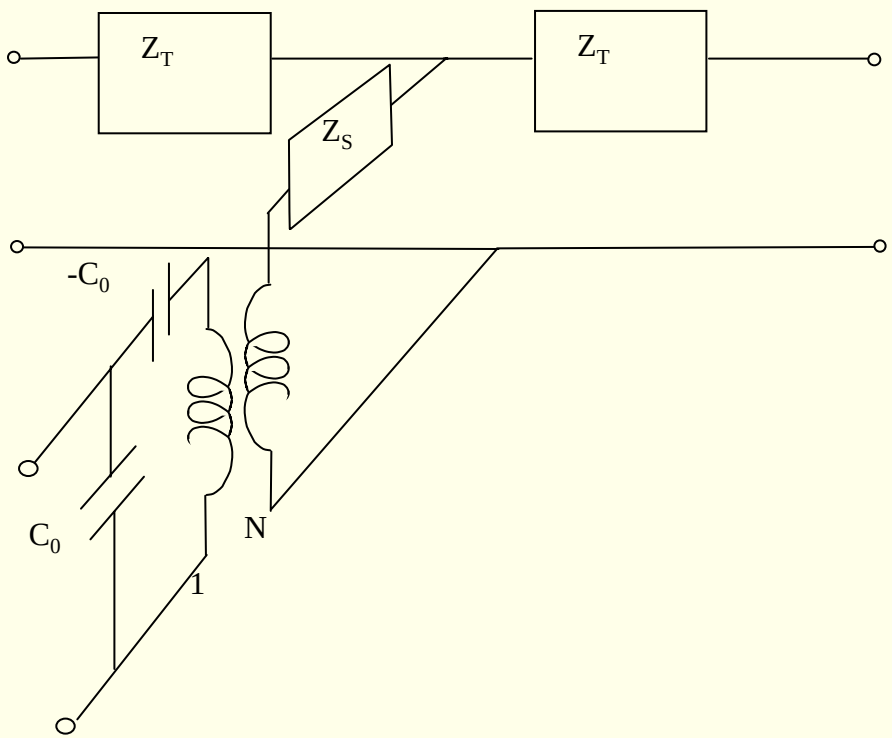




Network Representation

Solution to the wave equation
with open boundary conditions

Current/Voltage←Transformer→Force/Velocity



Mason's Model

$$\mathbf{N} = \mathbf{C}_0 \boldsymbol{h} \qquad \mathbf{C}_0 = \frac{\boldsymbol{\varepsilon}^S A}{t}$$

$$\mathbf{Z}_0 = \rho A \mathbf{v}^D = A\sqrt{\rho \mathbf{c}^D}$$

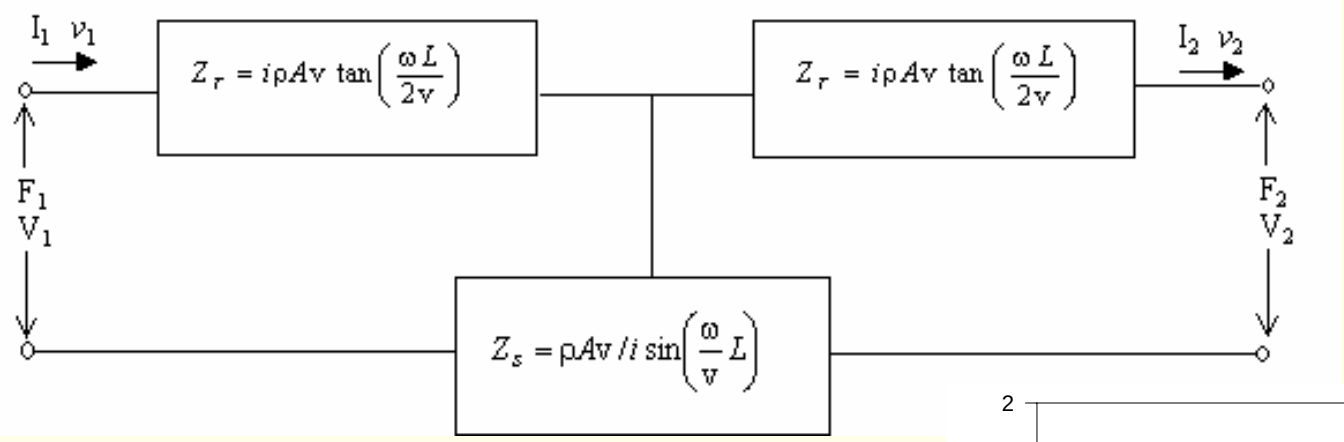
$$\Gamma = \frac{\omega}{\mathbf{v}^D} = \omega\sqrt{\frac{\rho}{\mathbf{c}^D}}$$

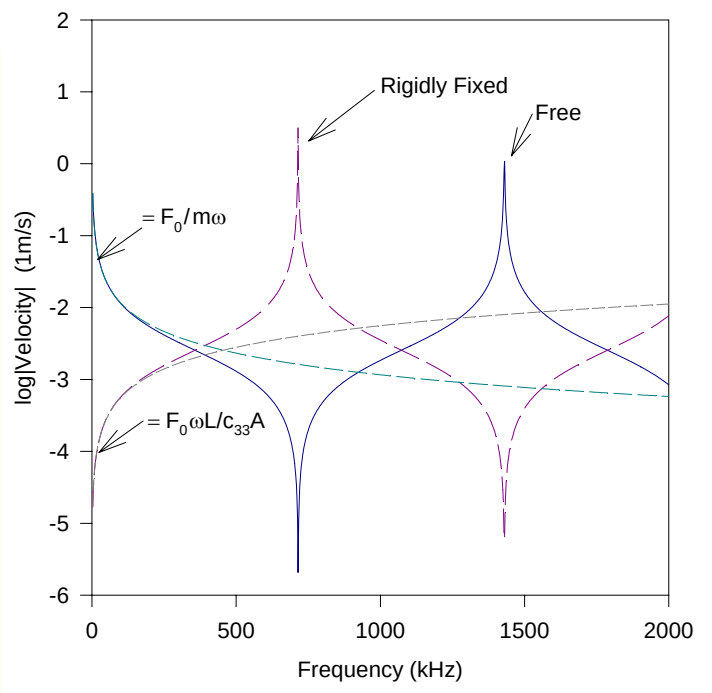
$$Z_T = i\mathbf{Z}_0 \tan(\Gamma t / 2)$$

$$Z_S = -i\mathbf{Z}_0 \csc(\Gamma t)$$

Acoustic Layer Networks

Solution to the wave equation with open boundary conditions

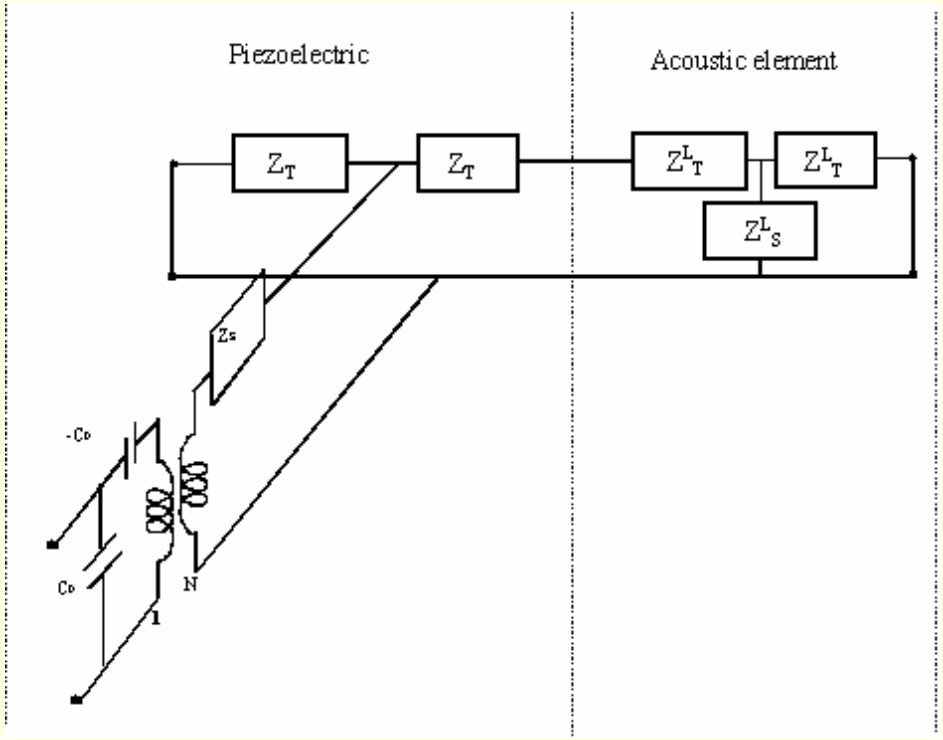


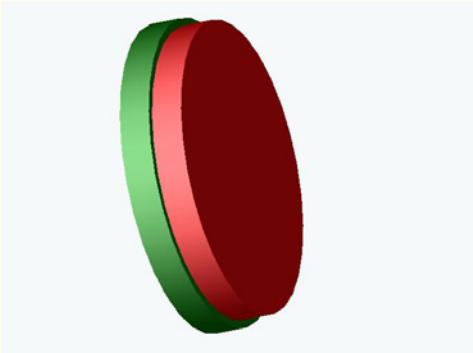


Force = Voltage
Velocity = Current

<u>Layer Parameters</u>
L thickness
A area
v velocity
ρ density

Combination of Piezoelectric and 1 layer





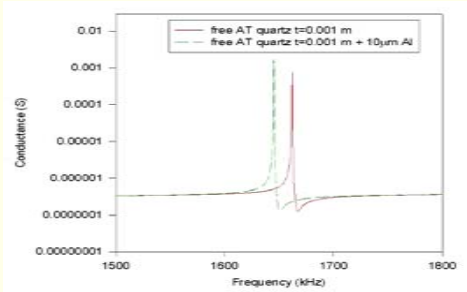
Acoustic Load Regimes

Depending on the acoustic length in the layer compared to the acoustic length of the piezoelectric. Three distinct loading regimes can load the piezoelectric differently. These include:

- Mass loading
- Elastic loading
- Radiation loading

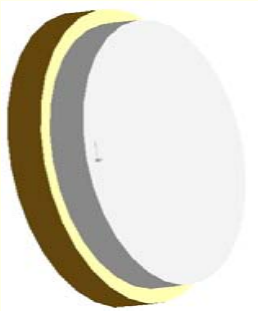
Mass Loading

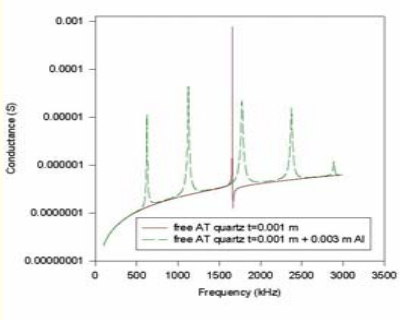
$$\mathbf{Z}_L = i\rho_l A_l \mathbf{v}_l \tan\left(\frac{\omega L}{\mathbf{v}_l}\right) = i\rho_l A_l \mathbf{v}_l \left(\frac{\omega L}{\mathbf{v}_l}\right) = im\omega$$



Elastic Loading

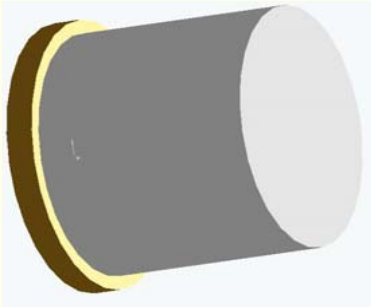
$$\mathbf{Z}_L = i\rho_l A_l \mathbf{v}_l \tan\left(\frac{\omega L}{\mathbf{v}_l}\right)$$

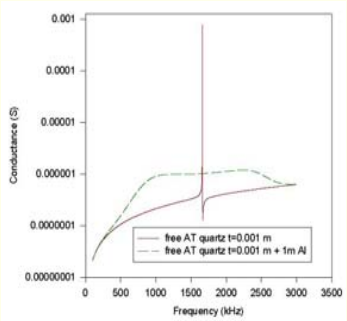




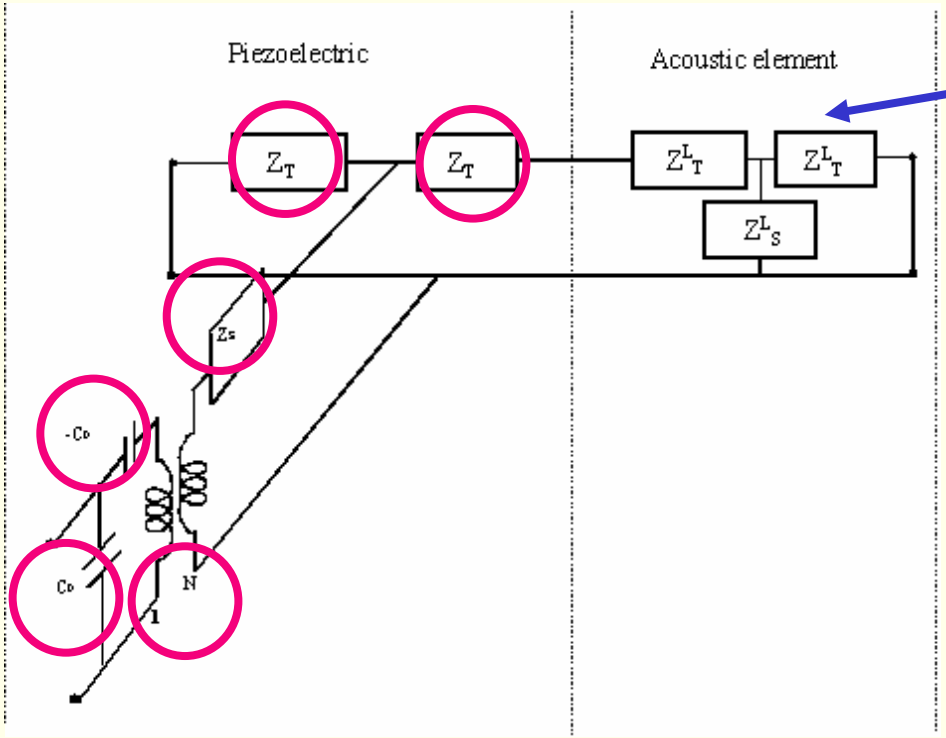
Radiation Loading

$$\mathbf{Z}_L = i\rho_l A_l \mathbf{v}_l \tan\left(\frac{\omega L}{\mathbf{v}_l}\right) = i\rho_l A_l \mathbf{v}_l (-i) = \rho_l A_l \mathbf{v}_l$$

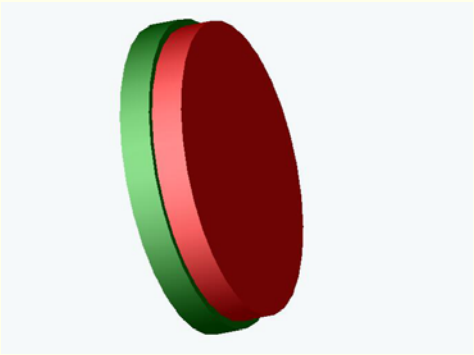




The constants (including loss) of the piezoelectric can be determine using curve fitting techniques prior to the addition of the layer



$$\mathbf{Z}_L = i\rho_l A_l \mathbf{v}_l \tan\left(\frac{\omega L}{\mathbf{v}_l}\right)$$



Known prior to deposition by analysis of free resonator

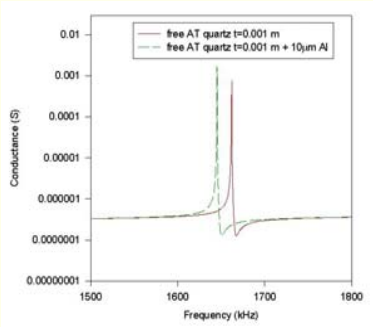
Since Z_C, Z_T, Z_S, N can be determined from the free spectra prior to deposition or attachment of the layer then we can determine the acoustic load directly for the layer using

$$\mathbf{Z}_L = \frac{\mathbf{Z}_T^2 - 2\mathbf{Z}_T\left(\mathbf{Z}_A - \mathbf{Z}_S\right)}{\mathbf{Z}_A - \mathbf{Z}_S - \mathbf{Z}_T}$$

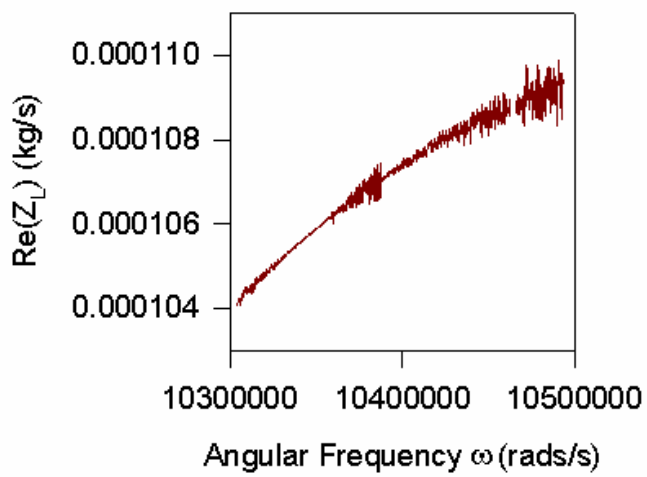
$$\mathbf{Z}_A = \frac{\mathbf{Z}_C \mathbf{N}^2}{\left(1 - \frac{\mathbf{Z}}{\mathbf{Z}_C}\right)}$$

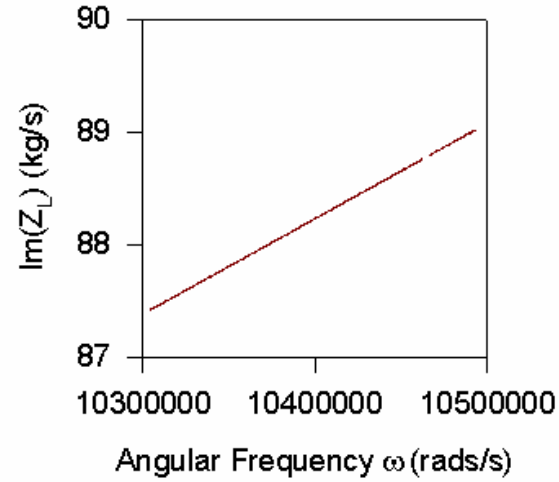
Where Z is the impedance spectra of the composite resonator

Transform applied to mass loading - QCM

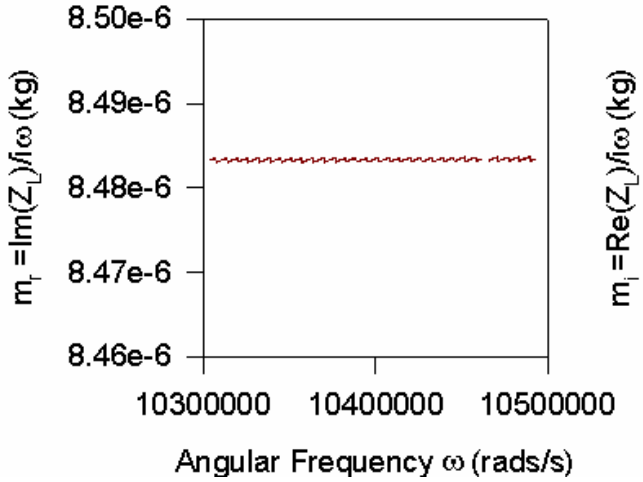


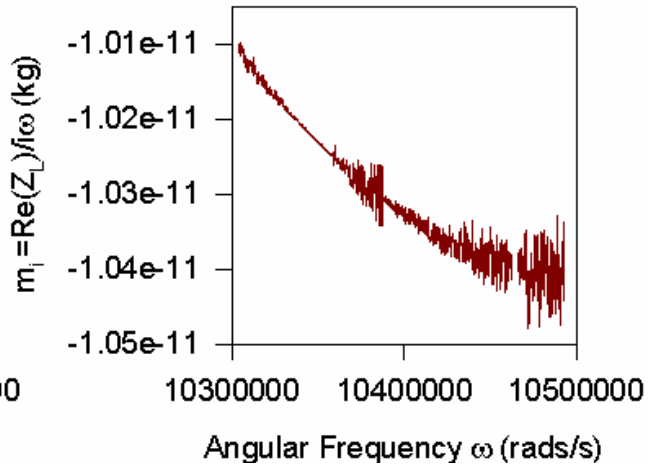
Z_L





$m^* = Z_L / i\omega$





Complex version of Sauerbrey equation

$$\mathbf{m}^*(f_{S2}) = m_0 \frac{(f_{s1} + \Delta f_{s1} i) - (f_{s2} + \Delta f_{s2} i)}{(f_{s1} + \Delta f_{s1} i)}$$

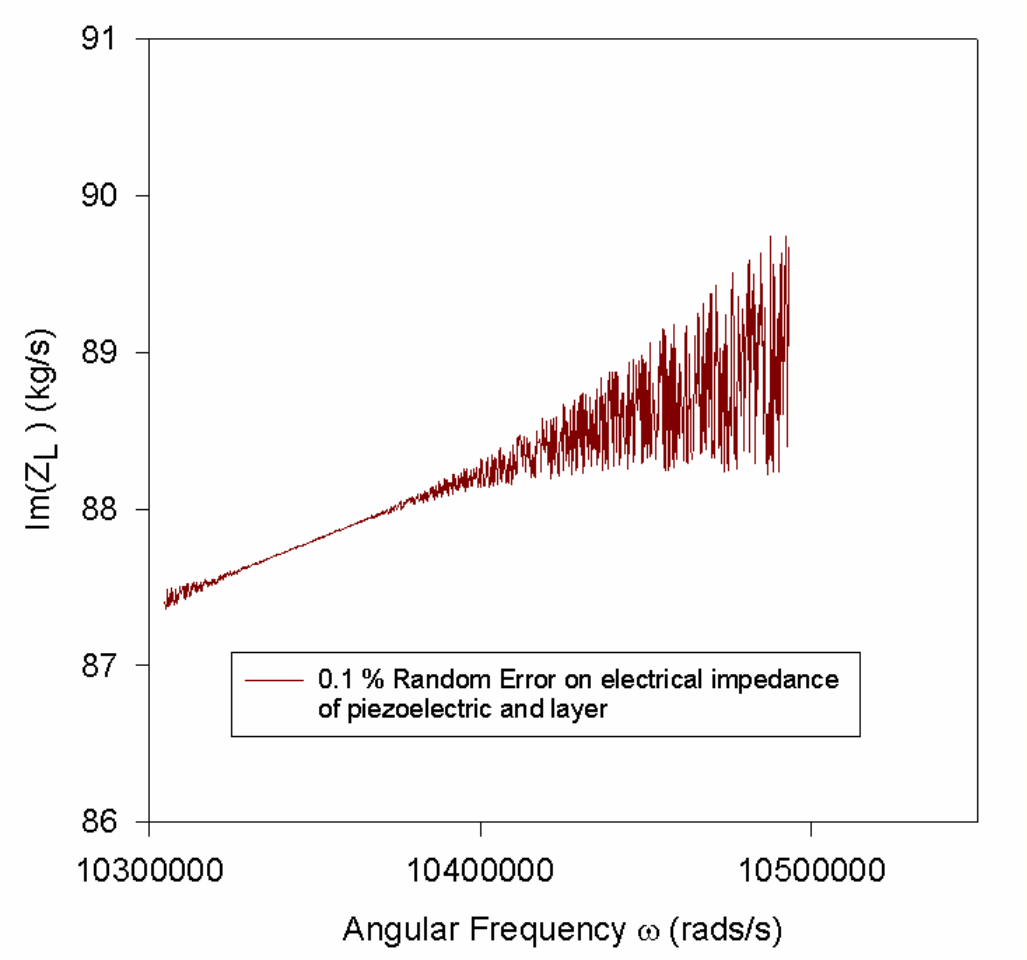
m* theory= (8.48-1.02x10^{-5}i) mg

m* transform = (8.48-1.03x10^{-5}i) mg

Error Propagation in Transform

Add 0.1 % Error to the composite resonator Impedance

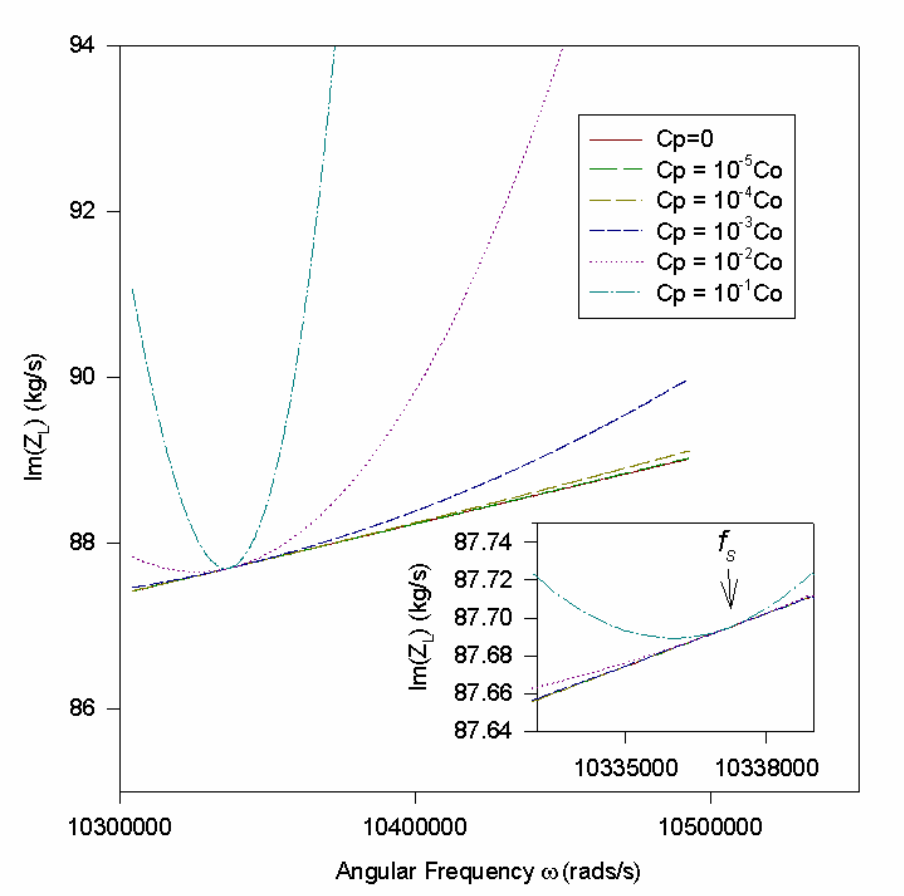
Error does not propagate into f_s



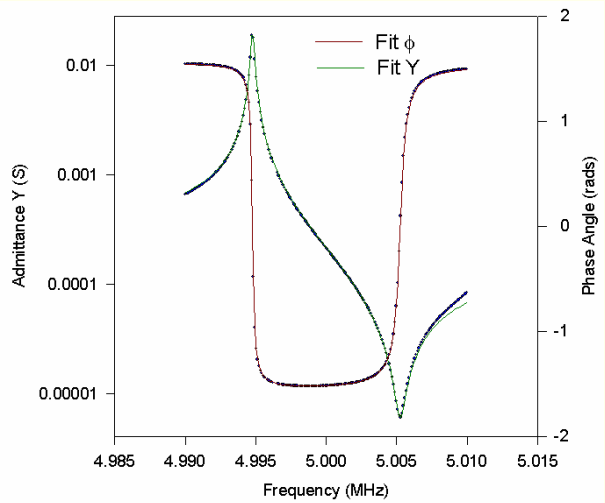
Error Propagation in Transform – Cont.

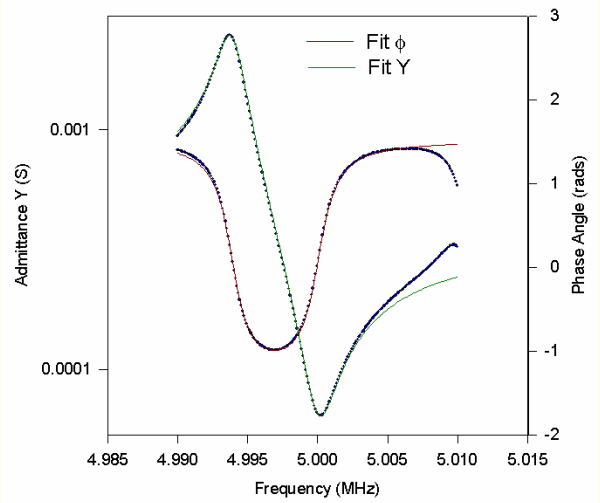
Add Stray capacitance to the composite resonator Impedance

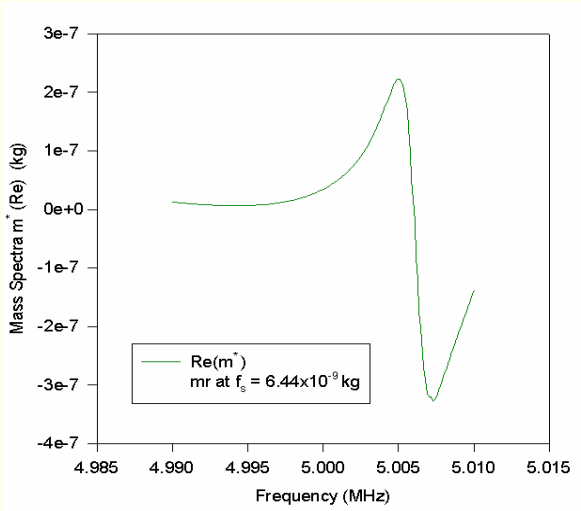
Again slope is constant about f_s

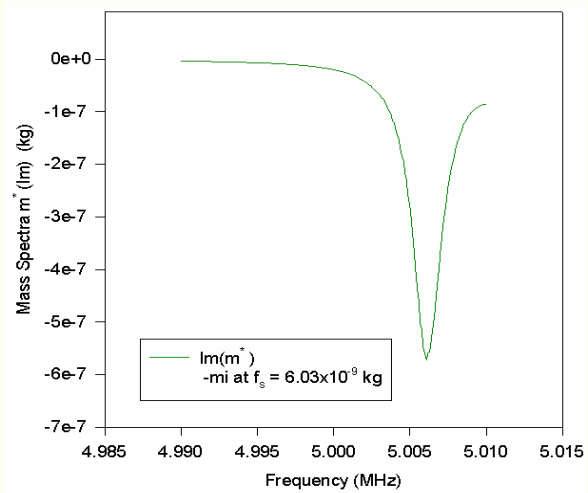


Transform applied to water load









	AT Cut Quartz Resonator in air
(F/m) ε^S (N/m^2) $\mathbf{c}^D$ (#) $\boldsymbol{k}$ (V/m) $\boldsymbol{h}$ ρ (kg/m^3)	$5.45933\times10^{-11}(1 - 0.02388i)$ $2.94472\times10^{10}(1 + 0.00012i)$ $0.0717744(1 - 0.00884i)$ $1.67\times10^{9}(1 + 0.02084\ i)$ 2650
t (m)	0.000333
A (m^2)	4.195×10^{-5}
m_0 (kg)	3.701×10^{-5}
$\boldsymbol{f}_{sq}$ (Hz) (quartz)	$4.99477\times10^{6} + 110.9i$
$\boldsymbol{f}_{s\,w}$(Hz) (quartz + water)	$4.99390\times10^{6} + 990.8i$
Δ**m** (kg) (Sauerbrey eq.)	$6.45\times10^{-9}-6.52\times10^{-9}{}_{i}$
Δ**m** (kg) (**m***(Re($\boldsymbol{f}_{Sq}$)) Figure 13.	$6.44\times10^{-9}-6.03\times10^{-9}{}_{i}$

Water Load is special case of Radiation Loading

$$\mathbf{Z}_L = i\rho_l A_l \mathbf{v}_l \tan\left(\frac{\omega L}{\mathbf{v}_l}\right) = i\rho_l A_l \mathbf{v}_l (-i) = \rho_l A_l \mathbf{v} = A_l (i\eta\omega\rho_l)^{1/2} = i m^* \omega$$

m*= $6.44\times10^{-9} - 6.03\times10^{-9}i$ kg with $\omega = 3.138\times10^{7}$ rads/s, $A = 4.195\times10^{-5}$ m^2, $\rho = 1000$ kg/m^3

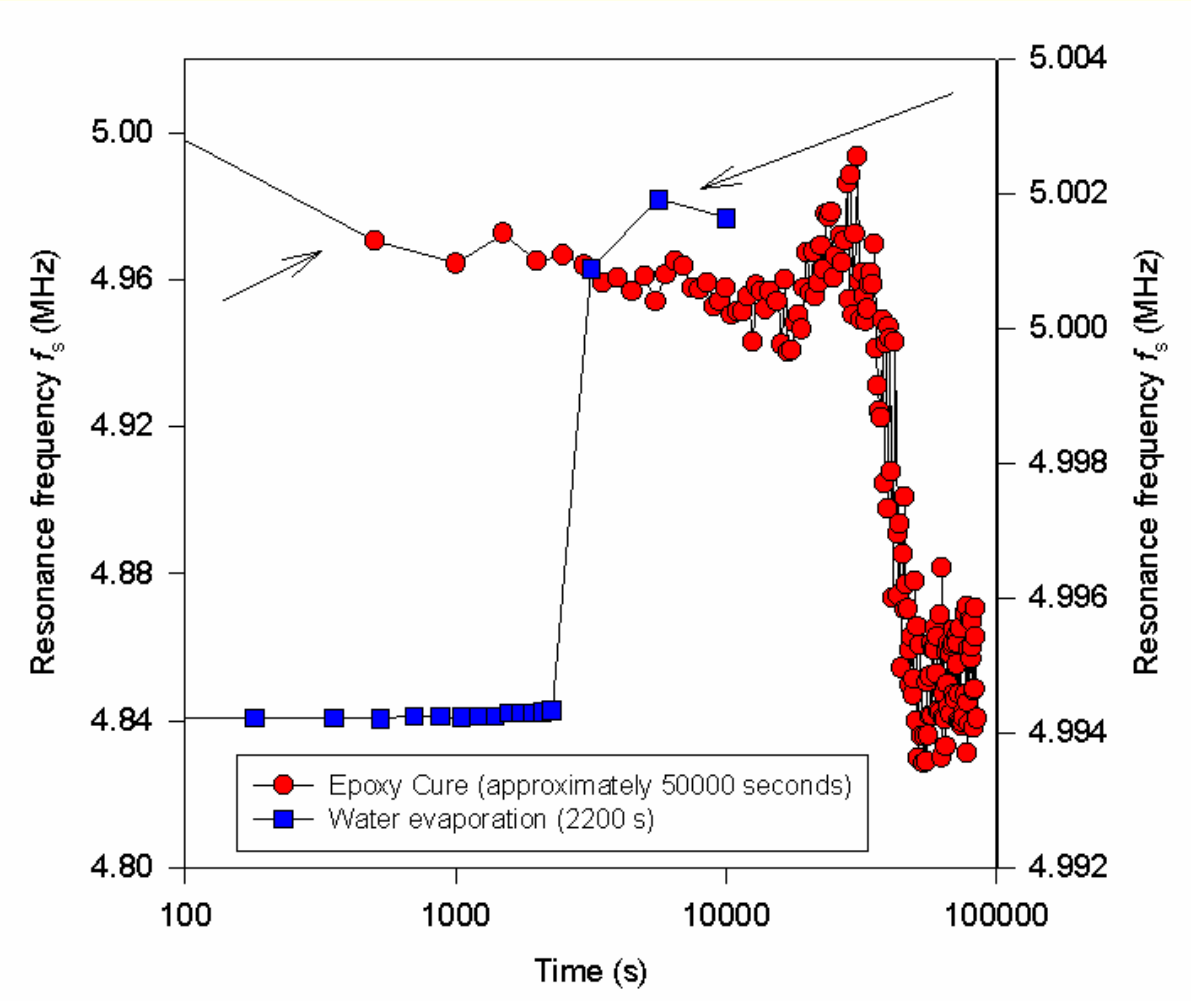
From previous table

$$\eta = 1.38(1+0.066i)\times10^{-3}\ \mathrm{Ns/m^2}$$

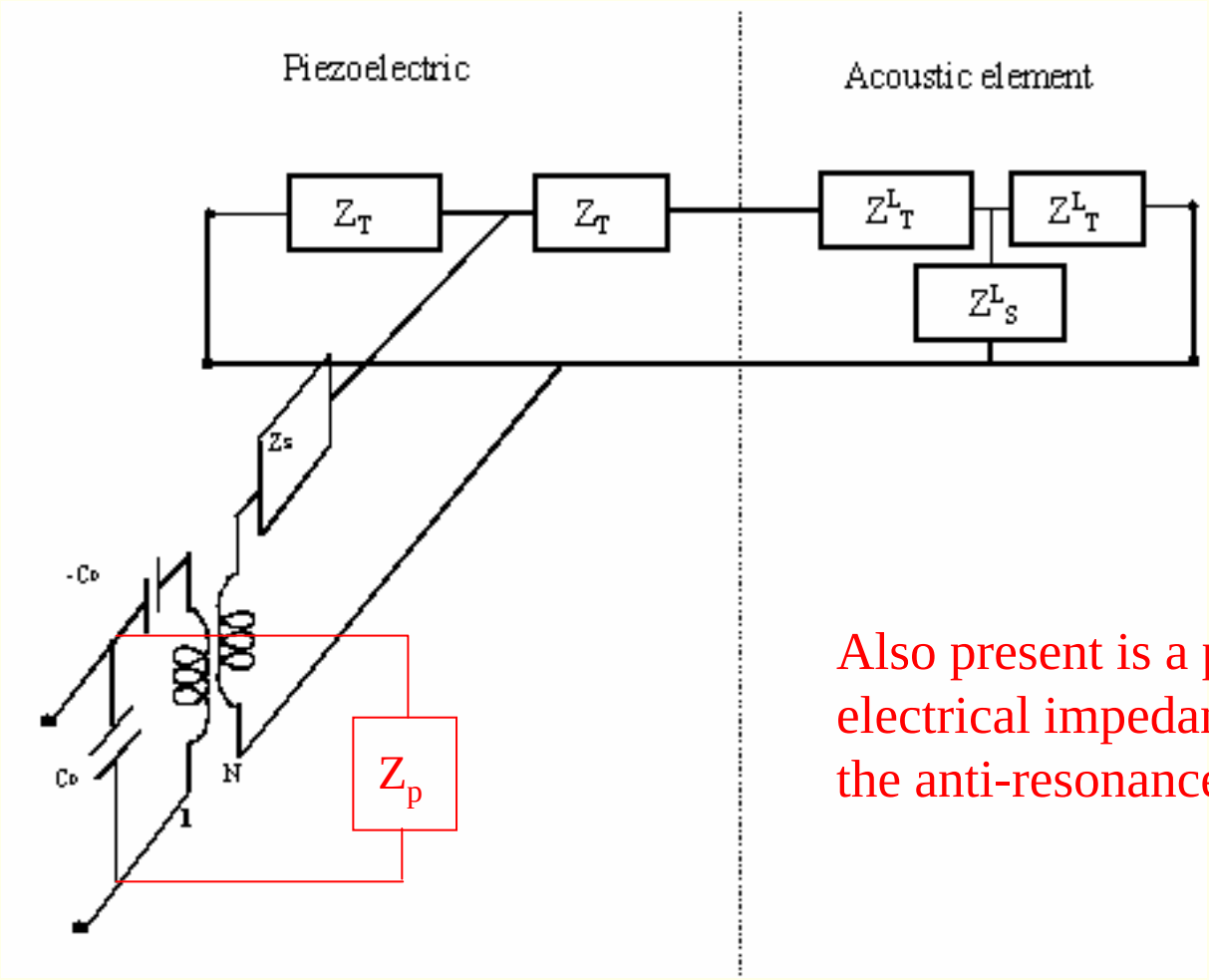
Book Value of $\eta = 1.12\times10^{-3}$ Ns/m^2 at 60 ^{o}F

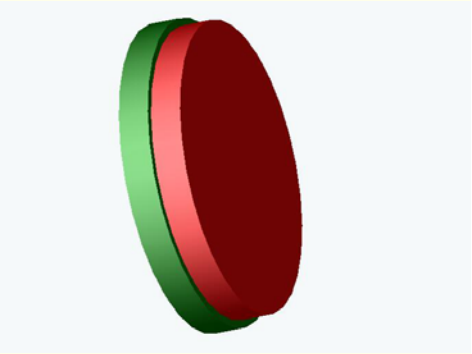
complex part of η determined above is a measure of the experimental error (no correction for parasitic electrical component), surface roughness and deviations from pure Newtonian fluid

Curing/evaporation studies



Combination of Piezoelectric and 1 layer





Also present is a parasitic electrical impedance that shifts the anti-resonance frequency f_a

Free SAW Resonance Equation

$$Y(\omega) = 2\frac{\omega_0 c_s K^2}{2\pi}\left(\tan\left(\frac{\pi\omega}{2\omega_0}\right)\sin\left(N\frac{\pi\omega}{\omega_0}\right)^2\right) + i\omega N c_s + \frac{i\omega_0 c_s K^2}{2\pi}\tan\left(\frac{\pi\omega}{2\omega_0}\right)\left(4N + \tan\left(\frac{\pi\omega}{2\omega_0}\right)\sin\left(N\frac{2\pi\omega}{\omega_0}\right)\right)$$

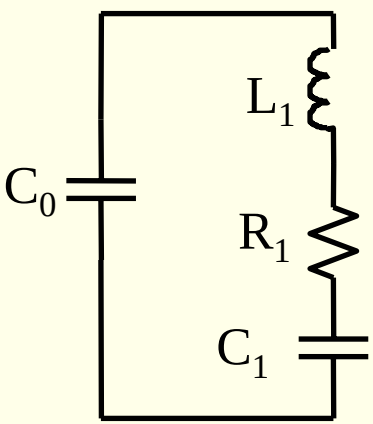
K = coupling factor

ω_0 = resonance frequency $\propto$ Rayleigh velocity

c_s = capacitance of IDT pair

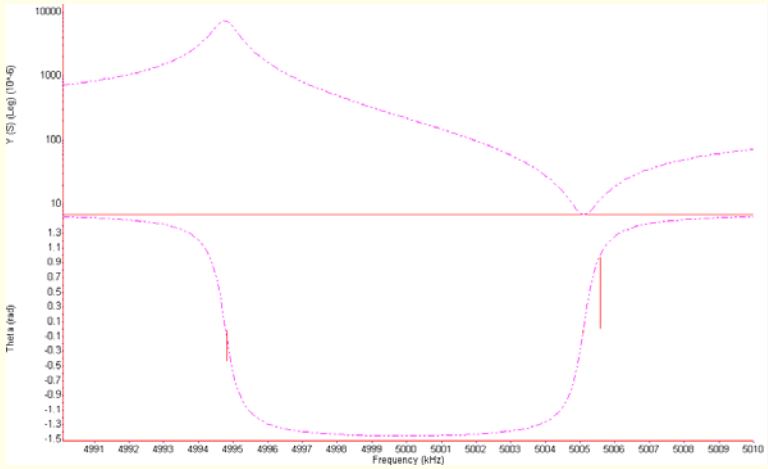
N = Number of electrode Pairs

SAW Resonator with reflectors (Simplest model BVD circuit)

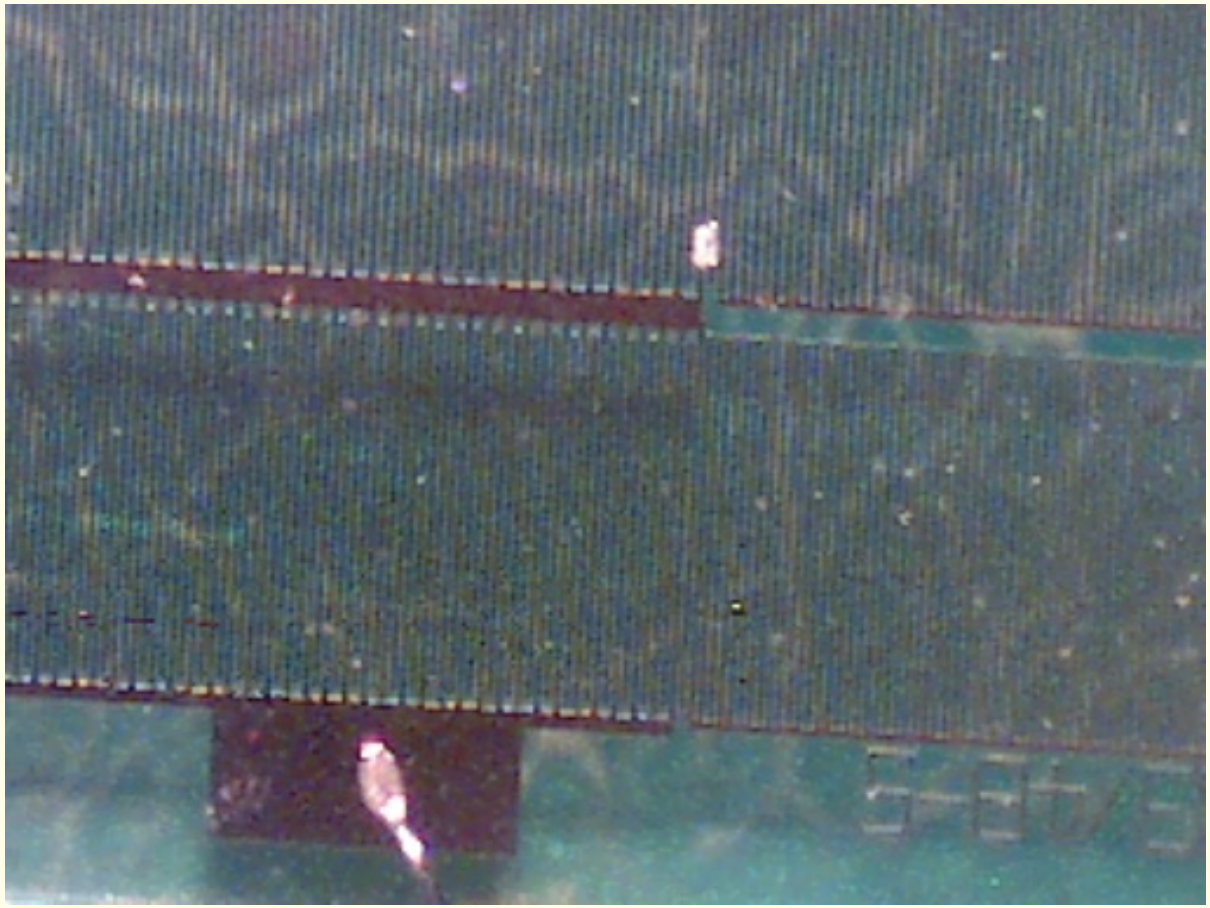


L_1, C_1, R_1 = Motional components

C_0 = Clamped capacitance

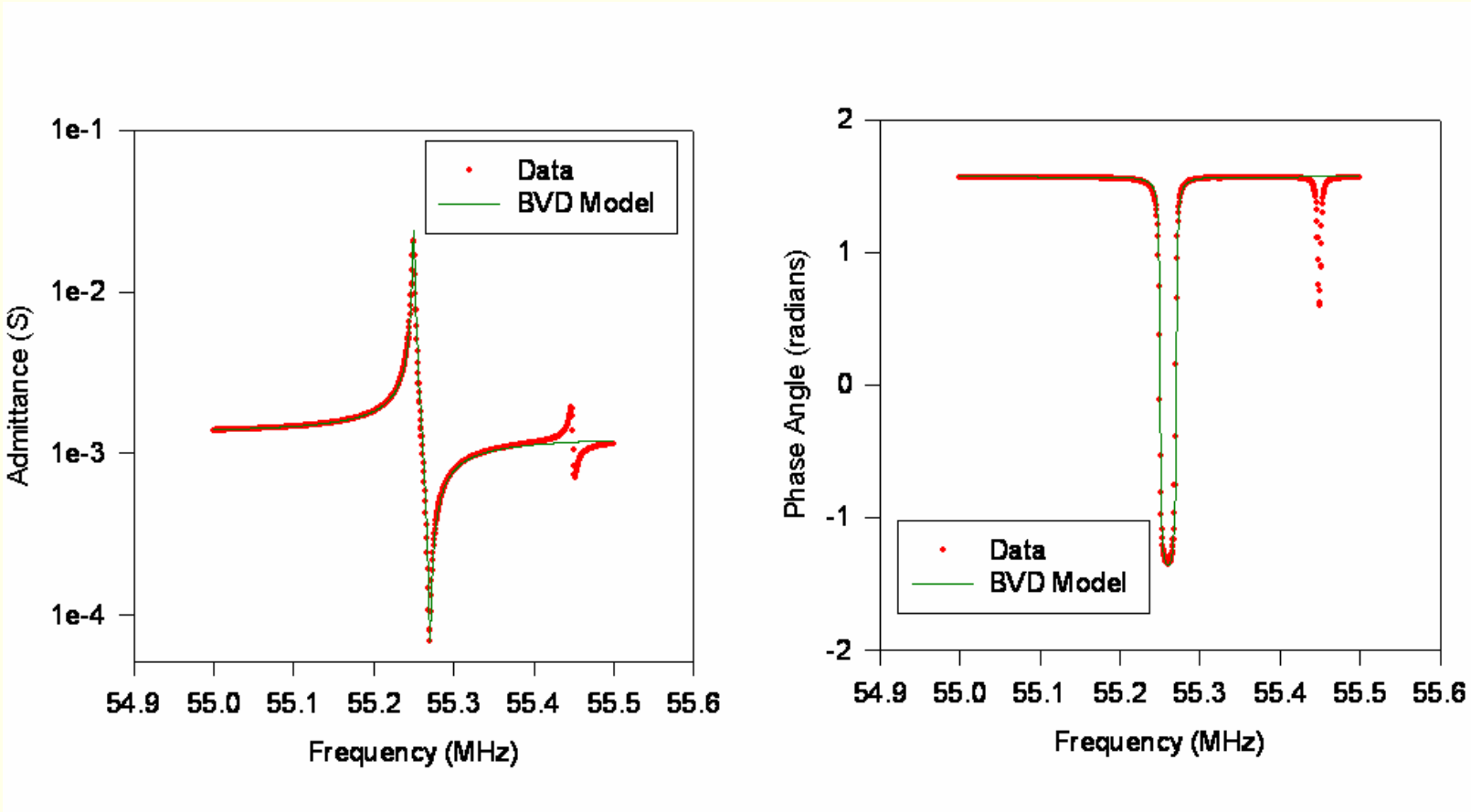


Saw Example



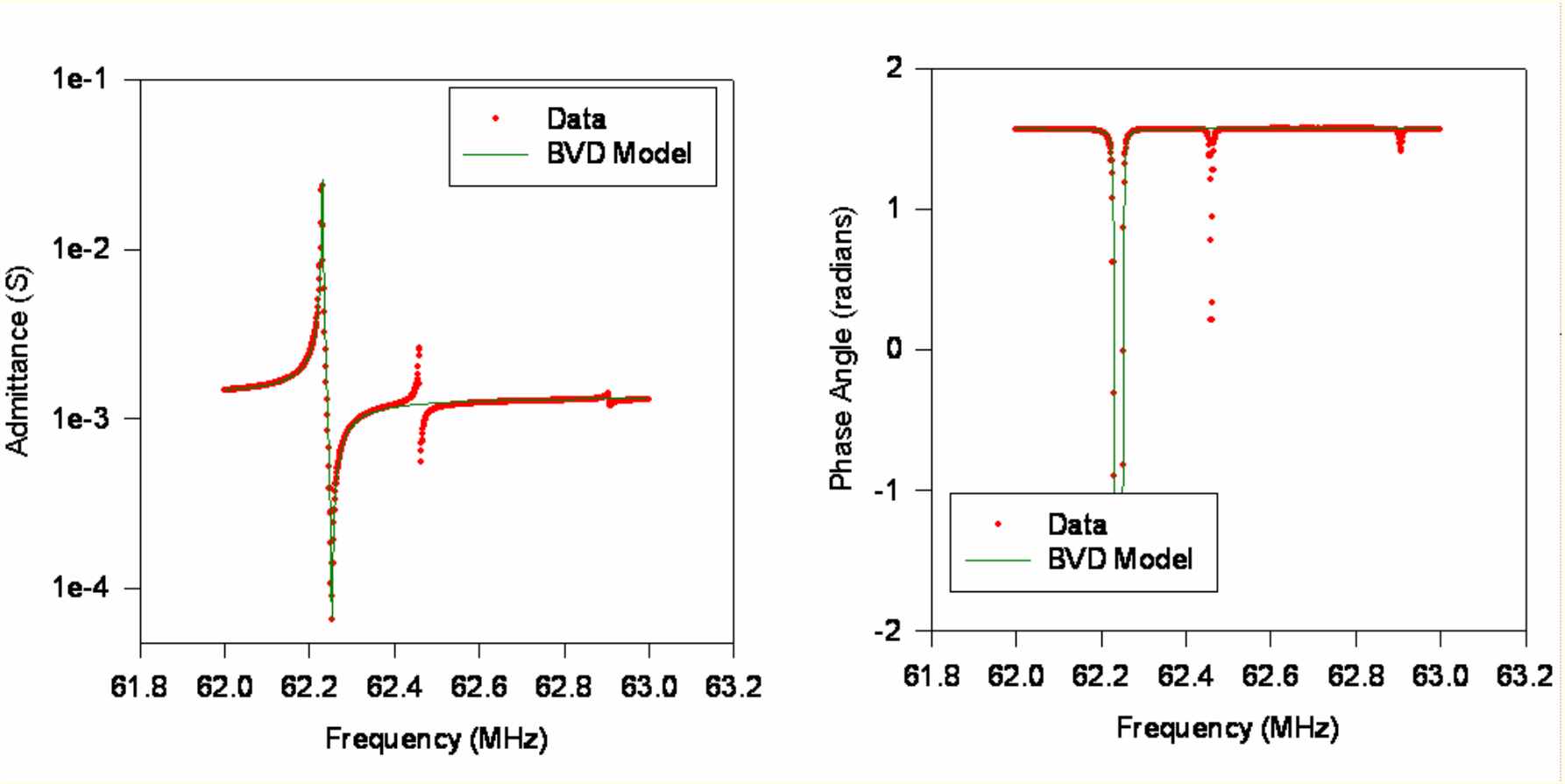
SAW Example (55.2 MHz)

Q = 22000



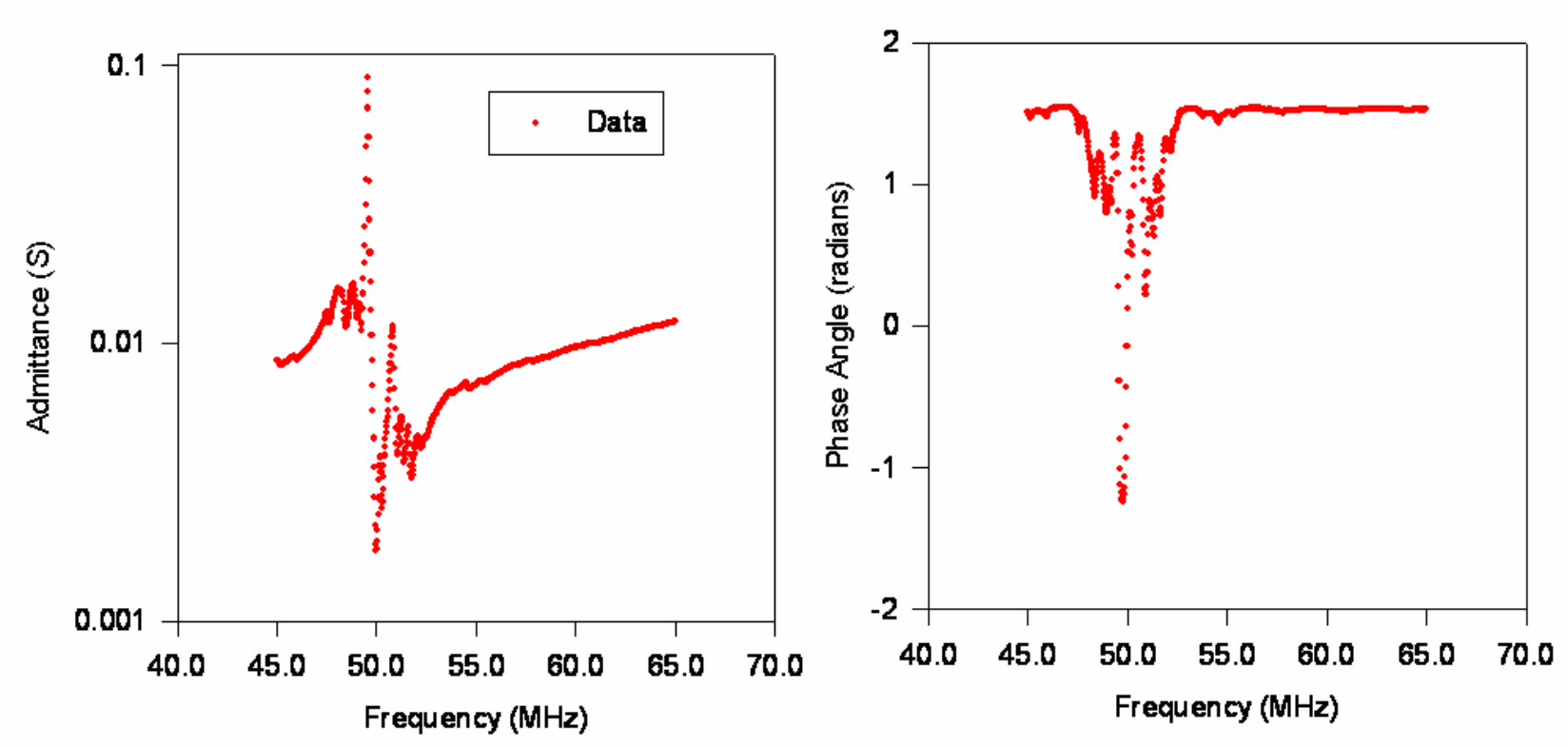
SAW Example (62.2 MHz)

Q = 27000



SAW Example (49.6 MHz) : Poor Quality resonance

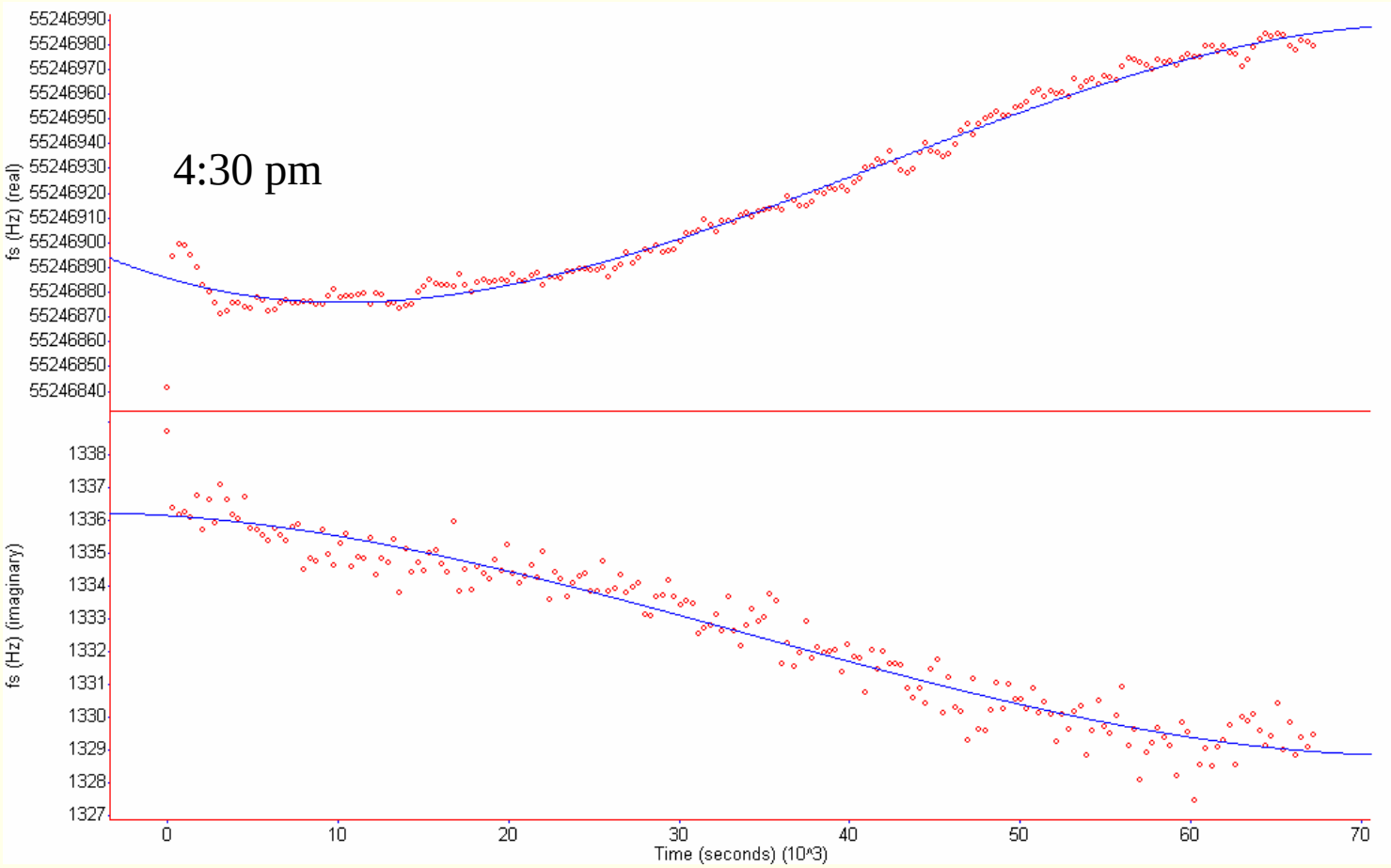
Q = 1000



SAW Stability (55.2 MHz)

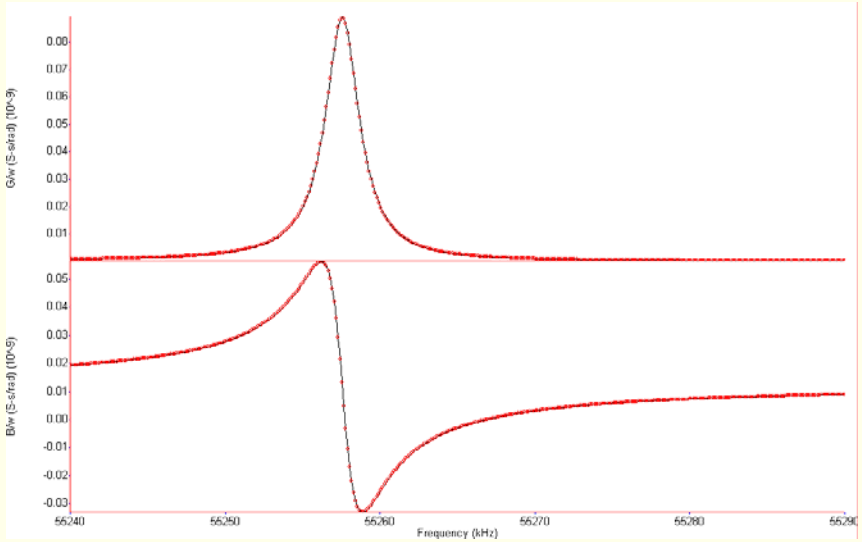
90 Hz over 18 hrs = 1.7 ppm

10:30 am

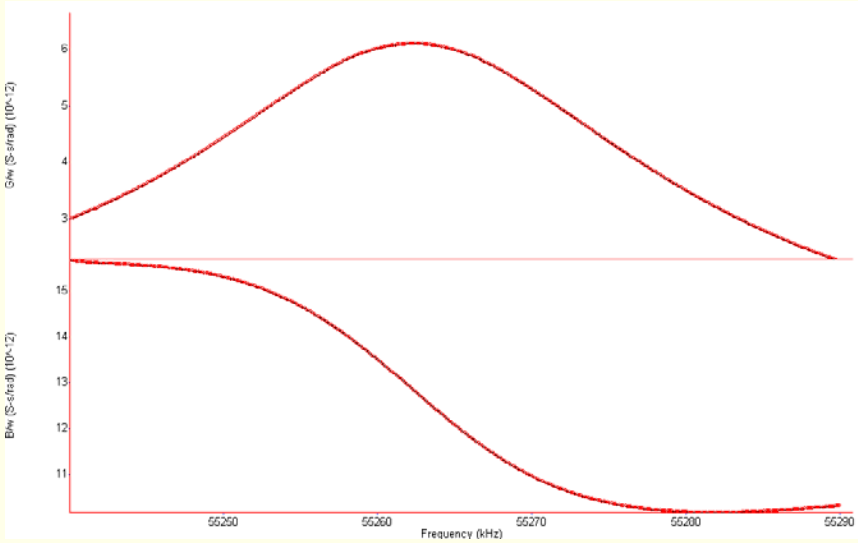


Example of SAW Sensor - Dust

Clean SAW Resonator



SAW Resonator with Limestone Dust



Passive Saw Interrogating Sensors

Table 1: SAW Properties of Common Materials (Yili Wu et al. "<u>Principals of Surface Acoustic Waves and its application in Electronic Technology</u>" Defense Industrial Press, PRC, 1983, (In Chinese)

Material	SAW velocity v (m/s)	Coupling K^2(%)	ε (pF/m)	α_T (ppm/^{o}C)
Quartz ST-X	3158	0.16	55	≈0
$LiNbO_3$ (YZ)	3485	4.5	460	91
$LiNbO_3$ (128°)	3921	5.7	-	57
ZnO	2715	1	-	40
$Bi_{12}GeO_{20}$ (100) (011)	1681	1.5	400	130

Correction Techniques for cross sensitivities

General Solution

$$\Delta f_i = k_{i,j} X_j$$

$$\begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \vdots \\ \Delta f_n \end{bmatrix} = \begin{vmatrix} k_{11} & k_{12} & k_{13} & k_{1j} & k_{1n} \\ k_{21} & k_{22} & k_{23} & k_{2j} & k_{2n} \\ k_{31} & k_{32} & k_{33} & k_{3j} & k_{3n} \\ k_{i1} & k_{i2} & k_{i3} & k_{ij} & \vdots \\ k_{n1} & k_{n2} & k_{n3} & \dots & k_{nn} \end{vmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{bmatrix} \Rightarrow \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{bmatrix} = \begin{vmatrix} k_{11} & k_{12} & k_{13} & k_{1j} & k_{1n} \\ k_{21} & k_{22} & k_{23} & k_{2j} & k_{2n} \\ k_{31} & k_{32} & k_{33} & k_{3j} & k_{3n} \\ k_{i1} & k_{i2} & k_{i3} & k_{ij} & \vdots \\ k_{n1} & k_{n2} & k_{n3} & \dots & k_{nn} \end{vmatrix}^{-1} \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \vdots \\ \Delta f_n \end{bmatrix}$$

Example

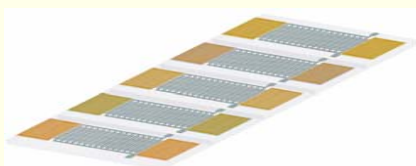
$$\frac{\Delta v}{v} = \frac{-\Delta\beta}{\beta} \approx \frac{\Delta f}{f} = k_m \frac{\Delta m}{m} + k_c \frac{\Delta c}{c} + k_T \frac{\Delta T}{T} + k_\gamma \frac{\Delta \gamma}{\gamma} + k_\sigma \frac{\Delta \sigma}{\sigma}$$

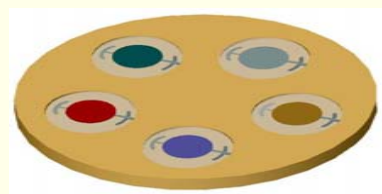
$$\begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \\ \Delta f_5 \end{bmatrix} = \begin{vmatrix} k_{m1} & k_{c1} & k_{T1} & k_{\gamma 1} & k_{\sigma 1} \\ k_{m2} & k_{c2} & k_{T2} & k_{\gamma 2} & k_{\sigma 2} \\ k_{m3} & k_{c3} & k_{T3} & k_{\gamma 3} & k_{\sigma 3} \\ k_{m4} & k_{c4} & k_{T4} & k_{\gamma 4} & k_{\sigma 4} \\ k_{m5} & k_{c5} & k_{T5} & k_{\gamma 5} & k_{\sigma 5} \end{vmatrix} \begin{bmatrix} \Delta m \\ \Delta c \\ \Delta T \\ \Delta \gamma \\ \Delta \sigma \end{bmatrix} \Rightarrow [\Delta f] = |k|[\Delta x_i] \Rightarrow \begin{bmatrix} \Delta m \\ \Delta c \\ \Delta T \\ \Delta \gamma \\ \Delta \sigma \end{bmatrix} = \begin{vmatrix} k_{m1} & k_{c1} & k_{T1} & k_{\gamma 1} & k_{\sigma 1} \\ k_{m2} & k_{c2} & k_{T2} & k_{\gamma 2} & k_{\sigma 2} \\ k_{m3} & k_{c3} & k_{T3} & k_{\gamma 3} & k_{\sigma 3} \\ k_{m4} & k_{c4} & k_{T4} & k_{\gamma 4} & k_{\sigma 4} \\ k_{m5} & k_{c5} & k_{T5} & k_{\gamma 5} & k_{\sigma 5} \end{vmatrix}^{-1} \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \\ \Delta f_5 \end{bmatrix}$$

The k factors above are material parameters so chose 5 sensors with different materials, cuts, or frequencies to get cross sensitivity matrix (1-5 designate specific sensor) (k normalized by dividing through by initial condition)

(Hietala et al. IEEE Trans UFFC **48**, pp. 262-267)

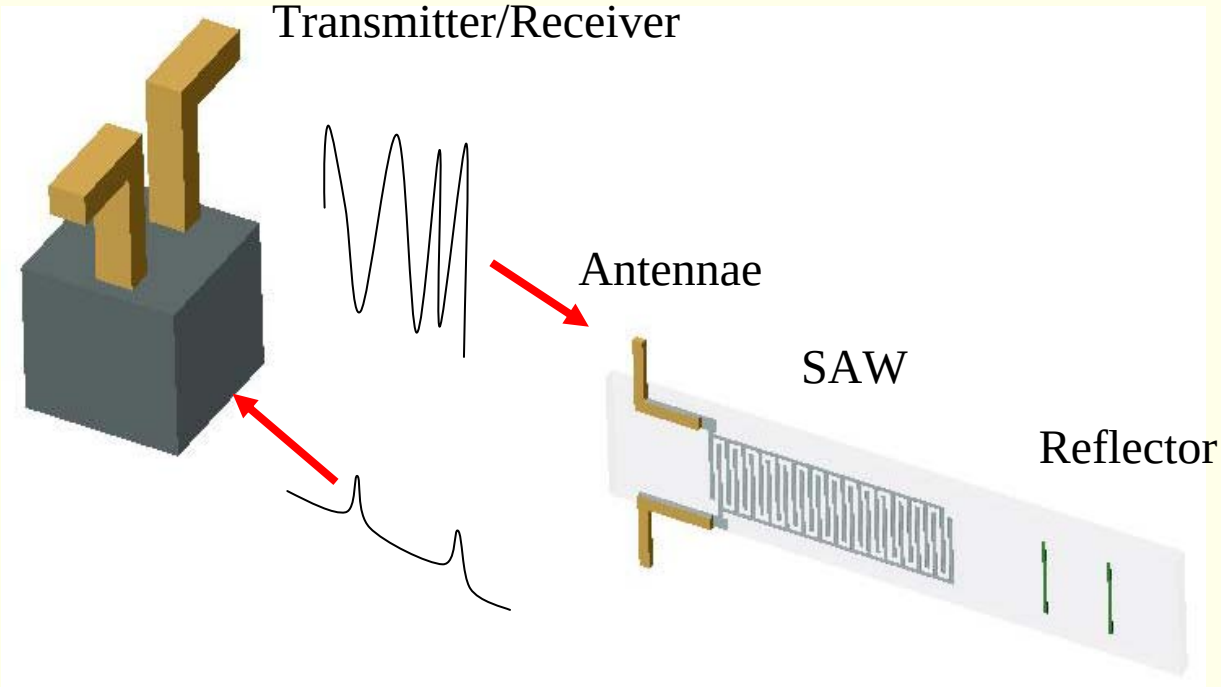
v = velocity
β = propagation factor
m = mass
c = elastic stiffness
T = Temperature
γ = Surface tension
σ = film stress





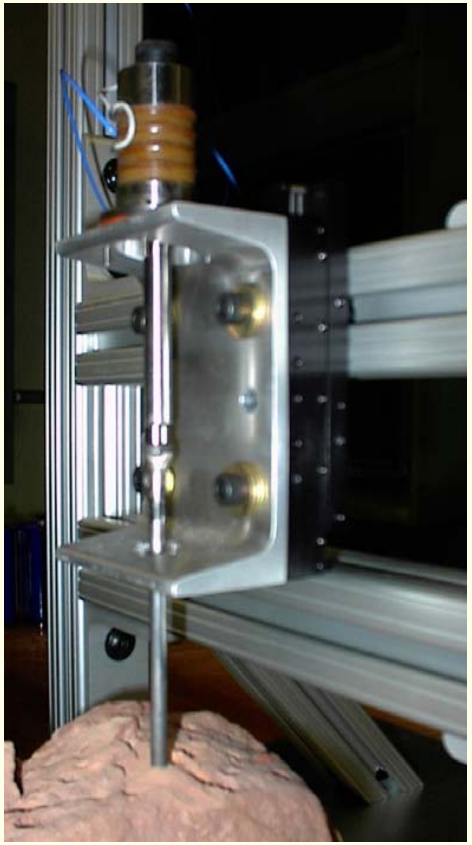
Passive Saw Interrogating Sensors

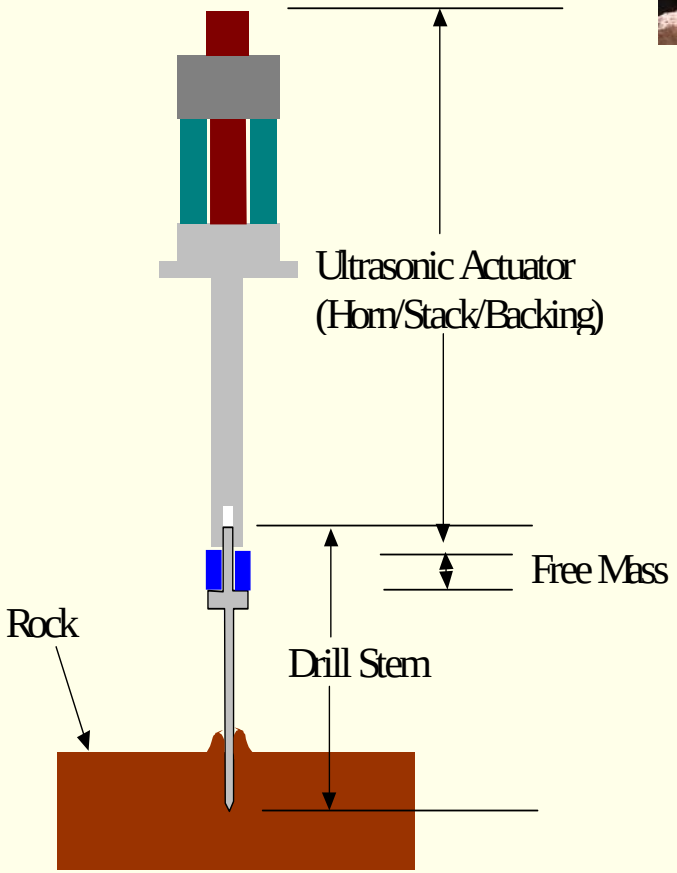
eg. Bao et al. IEEE Ultrasonics 1987, pp. 583-585



Phase difference in reflected pulse is a measure of the strain due to thermal expansion

USDC Technology



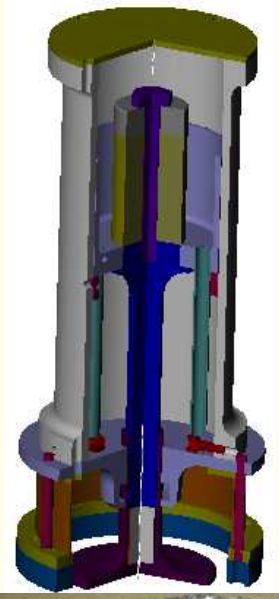


Device is driven at ultrasonic frequencies but produces sonic and ultrasonic Impacts.

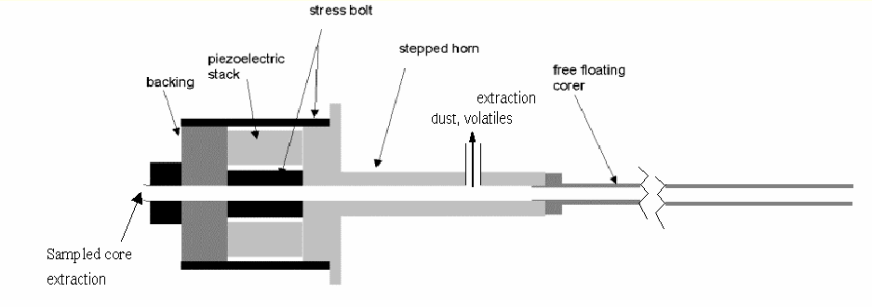
Various Applications of the USDC Technology

URAT

Ultrasonic Rock Abrasion Tool



Smart USDC with Integrated Sensors

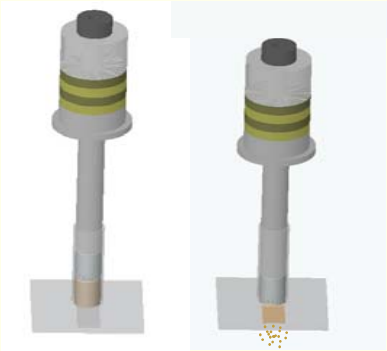


Folded Horns

Various Applications of the USDC Technology

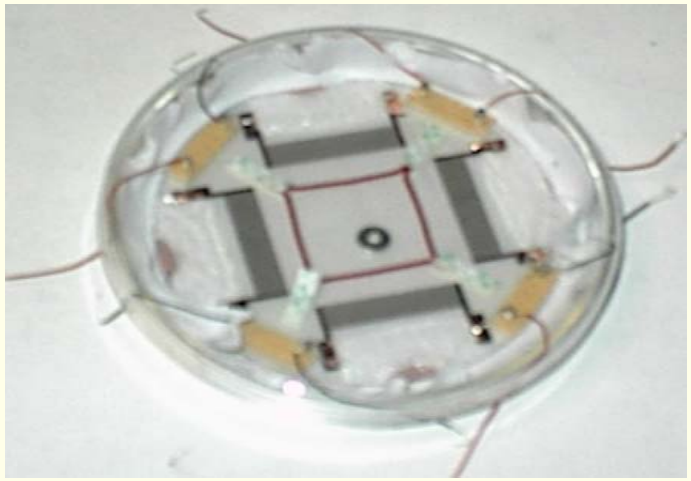
Deep Drill

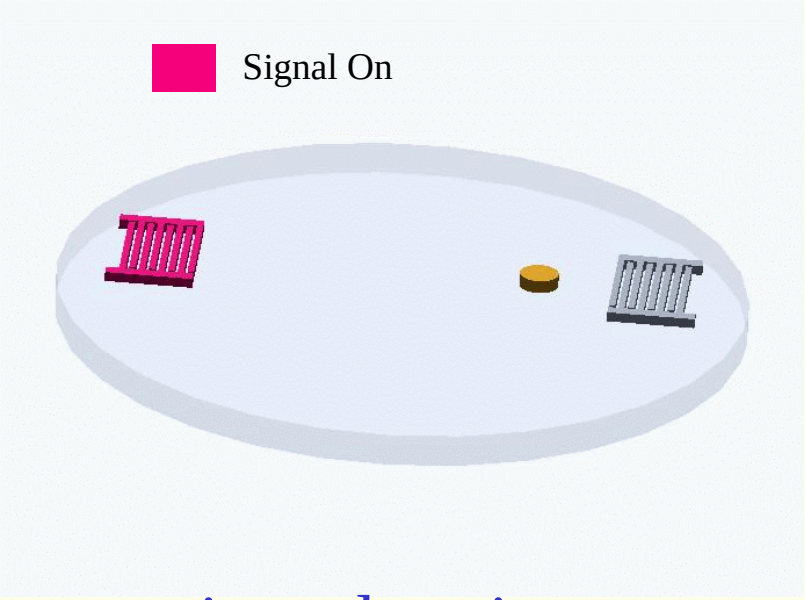
Rock Crusher



Powdering Tool

Surface Acoustic Wave (SAW) Motors





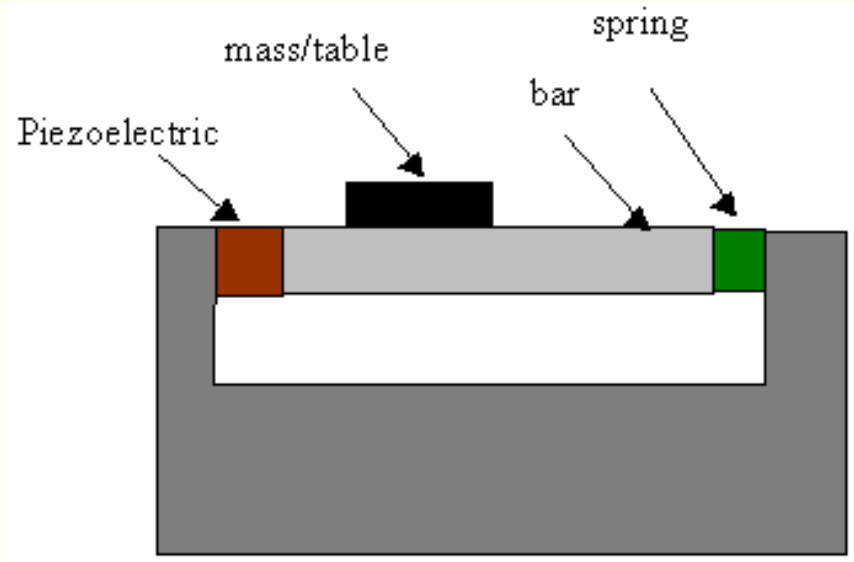
IDT excite a surface wave on piezoelectric substrate causes a mass to surf towards the source

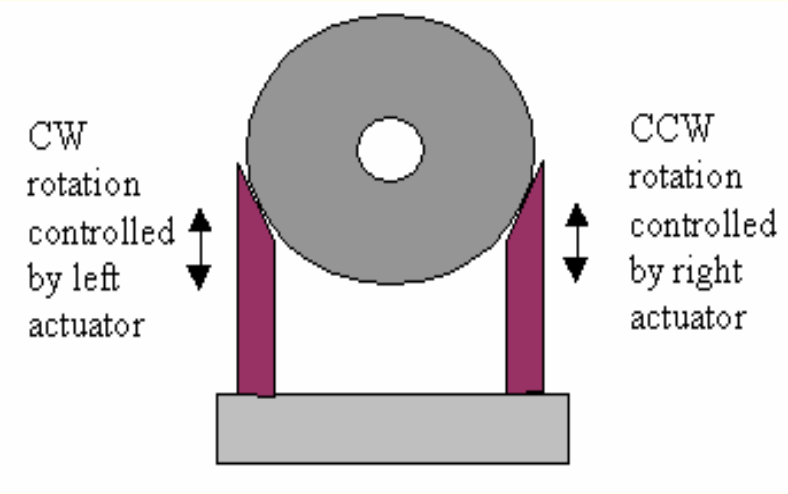
128° Y-cut $LiNiO_3$

V up to 10 m/s

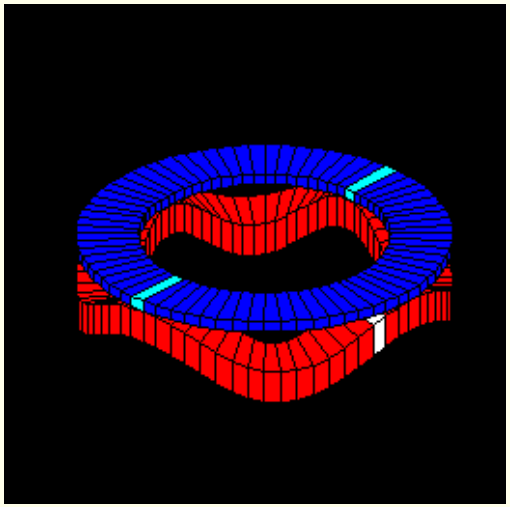
Force proportional to μN

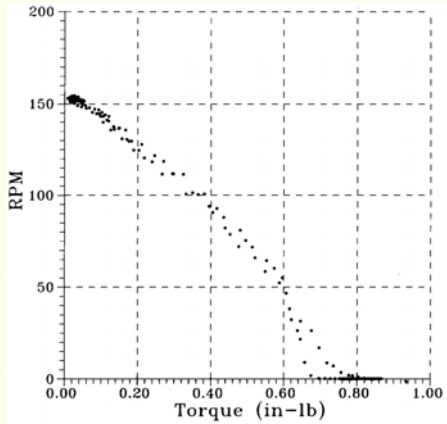
Piezoelectric Motors (Early Versions)

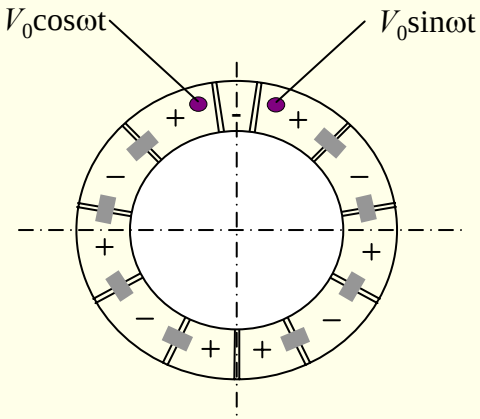




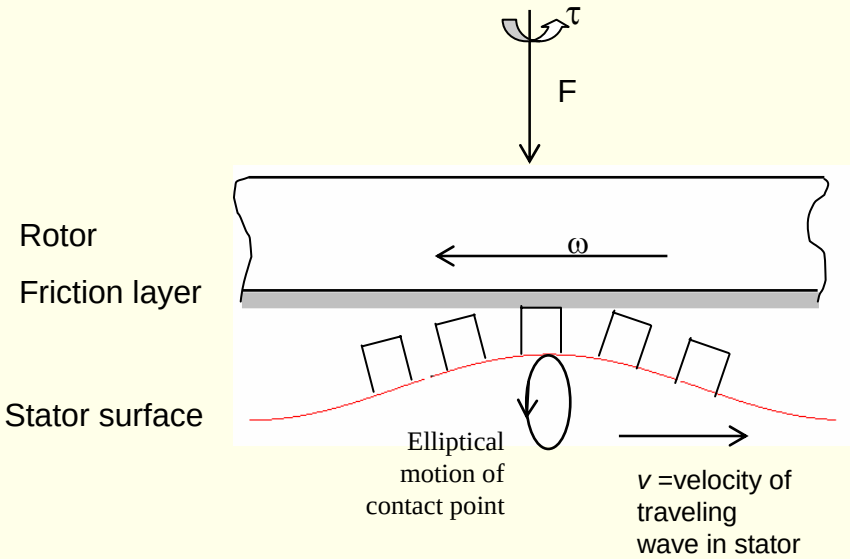
Ultrasonic Motors

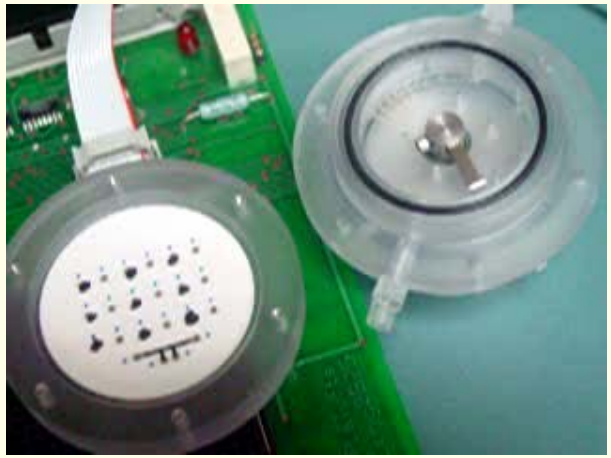






High Torque Density
Low RPM
Self Braking





Piezoelectric Pump

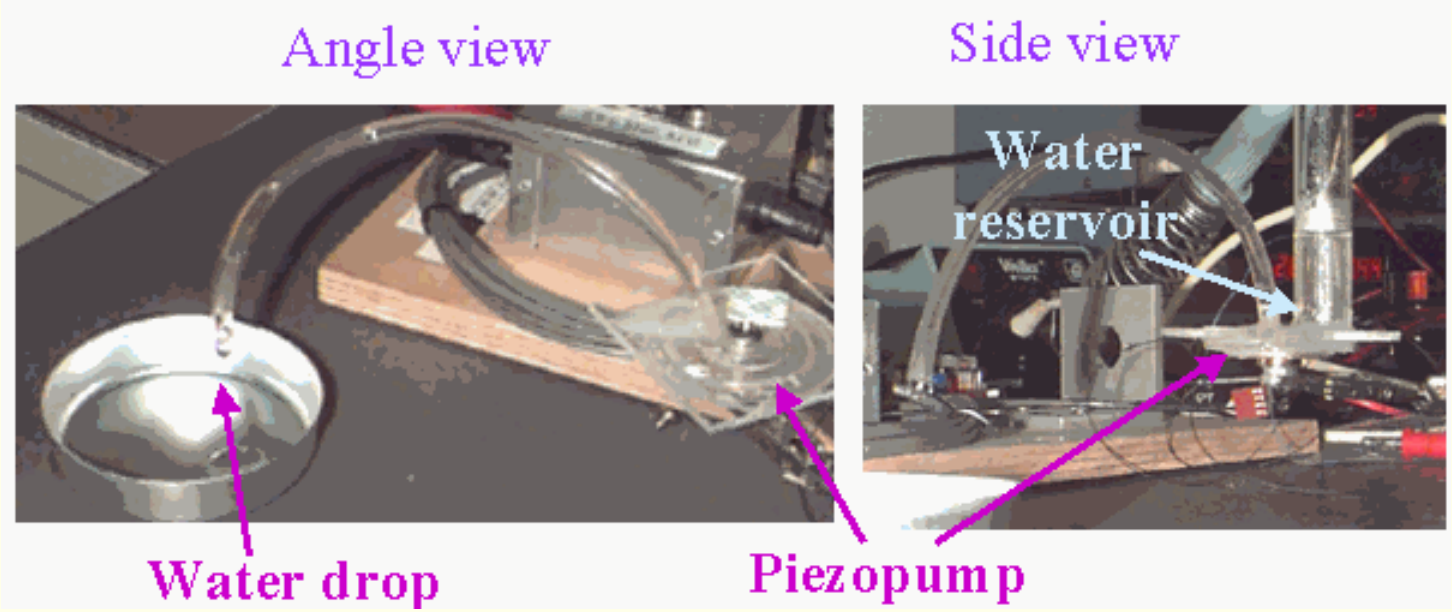
Current Specifications

4-5 cc/min

1100 Pa

No Moving Parts

Peristaltic



For More Information see

Devices -
http://ndeaa.jpl.nasa.gov/

Materials –
http://www.rmc.ca/academic/physics/ferroelectrics/Publications_e.html