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ELECTRO-CERAMIC PRODUCTS AND MATERIAL SPECIFICATION

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TABLE OF CONTENTS

L3Harris is one of the largest U.S. manufacturers of piezoelectric ceramic shapes and materials and welcomes both small and large volume customers.

Piezoelectric ceramic operations began in 1954 providing the development and manufacture of piezoelectric ceramic materials to the aerospace and defense industries. Since then, the uses for piezoelectric ceramic shapes, sensors, actuators and transducers have expanded to include many commercial and medical applications.

L3HARRIS IS ONE OF THE LARGEST U.S. MANUFACTURERS OF PIEZOELECTRIC CERAMIC SHAPES & MATERIALS

Piezo ceramic shapes are at the heart of many of today's newest technologies and L3Harris offers a broad product line with tailored solutions giving our customers the advantage of experience, expertise, quality, and improved time-to-market. We are vertically integrated and control each step in the manufacturing process. Our "Powder to Systems" approach means that no matter where on the vertical scale your requirements fall, L3Harris qualified and experienced teams understand the scope of the project.

This publication provides an introduction to some of the piezoelectric ceramic products available from L3Harris and methods for assessing your needs and defining the parameters of your product requirements. Information on our capabilities and ordering process is included.

PIEZOELECTRICITY

Piezoelectricity is a property of certain crystalline materials whereby an electrical charge is generated proportionally from a mechanical stress (sensor), and conversely a mechanical strain is generated by the application of an electric field (actuator). The word is derived from the Greek piezein, which means to squeeze or press. Piezoelectric ceramics transform mechanical energy to electrical energy and vise versa in a number of modes. Figure 1 shows this transformation in (a) thickness/length, (b) radial, (c) thickness shear, and (d) bending modes. Due to this proportional sensing and actuating transduction in various modes, piezoelectric ceramics have found numerous applications.

There are thirty-two crystallographic point groups, often termed crystal classes. Twenty-one of these crystal classes have no center of symmetry, and of these, twenty exhibit direct piezoelectricity. If the dipole can be reversed by the application of an electric field, the material is said to be ferroelectric.

Crystals that display piezoelectric properties experience a change in polarization due to mechanical stress. Figure 2 shows the intrinsic piezoelectric effect for lead zirconate, where the charged zirconium ion (Zr) shifts relative to the center position with the application of stress.

When initially fabricated, polycrystalline piezoelectric ceramic materials have a random orientation of grains and domains, and therefore have no net polarity or piezoelectric effect. However, analogous to the magnetizing of a permanent magnet, polarity can be imparted to the ceramic by "polarizing" or "poling" with the temporary application of a strong electric field at an elevated temperature, Figure 3.

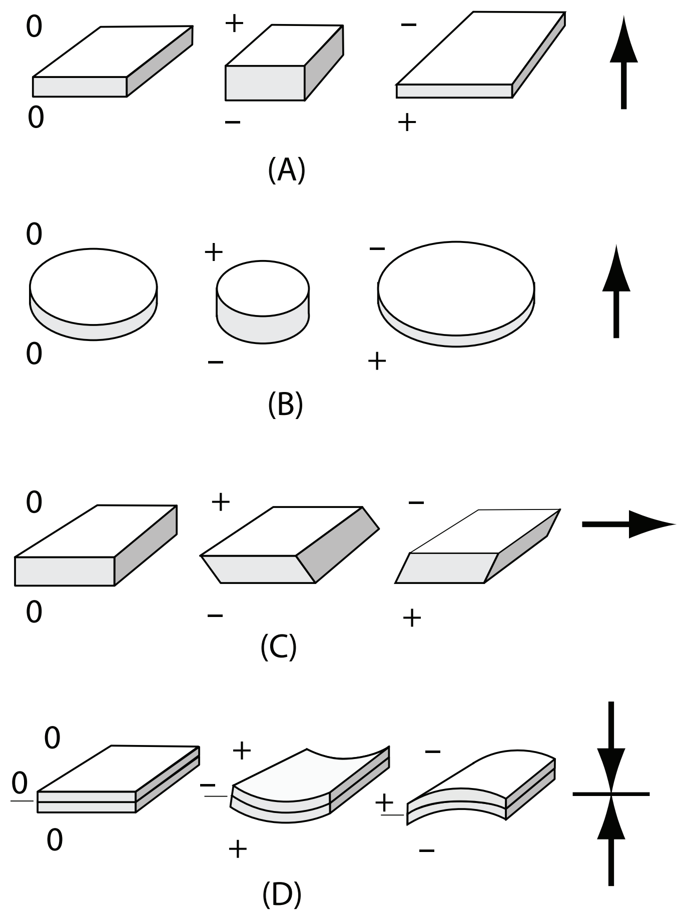


Figure 1: *Basic piezoelectric transduction in (A) thickness and length, (B) radial, (C) thickness shear, and (D) bending modes. The arrows represent the direction of polarization and the (+) and (-) are the applied fields.*

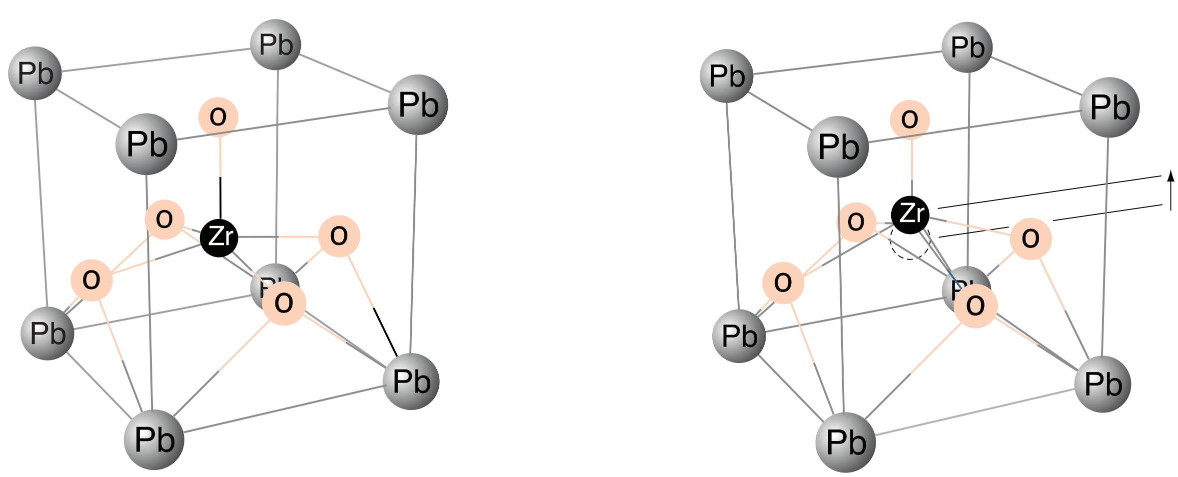
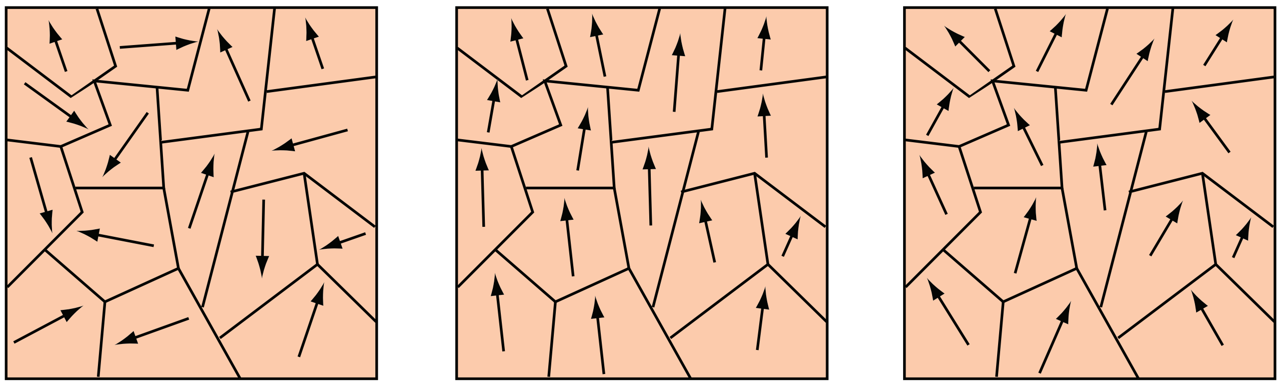


Figure 2*: Intrinsic piezoelectric effect in lead zirconate, where the charged zirconium ion (Zr) moves relative to the center position*

Figure 3 shows the polarization of a piezoelectric ceramic from its (A) randomly oriented domain state to a (B) net positive polarity state. After "poling," there is a remnant polarization and strain in the material that relaxes or ages with time, as shown in (C).



(A) Random As-Fired Ceramic

(B) Net Positive As-Polarized Ceramic

(C) Relaxed Positive Aged Ceramic

Figure 3: *Polarization of polycrystalline piezoelectric ceramic causes (A) the as-fired random domain polarity to align to (B) a net positive polarity, which (C) relaxes or ages over time*

DEFINITIONS

Symbols

	a	Mean Radius
	A	Area
	cij	Elastic stiffness constant
	C	Capacitance
	dmi	Piezoelectric constant
(superscript or subscript)	*D*	At constant electric displacement
	Di	Electric displacement component
	emi	Piezoelectric constant
	Ec	Coercive field
(superscript or subscript)	*E*	At constant electric field
	Ei	Electric field component
	f	Frequency
	fa	Antiresonance frequency (zero reactance)
	fr	Resonance frequency (zero susceptance)
	fm	Frequency of minimum impedance
	fn	Frequency of maximum impedance
	fp	Frequency of maximum resistance (parallel resonance)
	fs	Frequency of maximum conductance (series resonance)
	g_{mi}	Piezoelectric constant
	h_{mi}	Piezoelectric constant
	K	Relative dielectric constant
	k_{31}	Rod extensional coupling factor with transverse excitation
	k_{33}	Rod extensional coupling factor with longitudinal excitation
	k_{15}	Thickness-shear coupling factor

	k_{eff}	Effective coupling factor
	k_p	Planar coupling factor
	k_t	Thickness-extensional coupling factor
	l	Length
	N	Frequency constant
	P_r	Remnant polarization
	q	Charge
	Q_m	Mechanical quality factor
	s_{ij}	Elastic compliance constant
(superscript or subscript)	S	At constant strain
	S_i	Strain component
(superscript or subscript)	T	At constant stress
	T_i	Stress component
	T_c	Curie temperature
	t	thickness
	V	Voltage
	Z_m	Impedance at f_m
	Z_n	Impedance at f_n
	β_{mn}	Impermittivity component
	ε_o	Permittivity of free space *($\approx 8.8542 \cdot 10^{-12}$ F/m)*
	ε_{mn}	Permittivity component
	φ	Electric potential
	ρ_e	Free electric charge density
	ρ	Mass density
	σ^p	Planar Poisson's ratio

Three orthogonal axes are represented by subscript values 1 – 3. By convention, axis 3 is the direction of polarization of ferroelectric ceramic. A reduced subscript notation is used in which subscripts 4 – 6 indicate stress or strain in shear form about axes 1 – 3, respectively. This is illustrated in Figure 4.

The dielectric constant may be written with a single subscript as the only non-zero terms in the permittivity matrix of poled ferroelectric ceramic are along the diagonal and so have repeated indices.

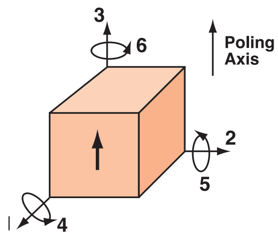


Figure 4: *Axis notation for polarized piezoelectric ceramics*

In reduced subscript notation, electromechanical quantities can have two numerical indices. The first indicates the electrical direction and the second indicates the mechanical direction. Some special cases use a letter subscript such as p (planar mode), h (hydrostatic), or t (thickness mode). Examples are given in Table 3, p11.

Electrical

Electric field – The electric force per unit charge and is given by the negative gradient of electric potential, when magnetic effects can be ignored.

$$E = - grad\ \varphi$$

Electric displacement – The electric displacement is defined by the relation:

$$D = \varepsilon_o E + P$$

Where P is polarization. It is related to free charge density by Gauss's Law. For an infinite parallel plate capacitor its magnitude is given by charge per unit area:

$$|D| = q / A$$

Gauss's Law – The Maxwell equation

$$div\ D = \rho_e$$

Remnant polarization – Remnant polarization (Figure 5) is the polarization that remains when the electric field is reduced to zero.

Coercive field – The coercive field (Figure 5) is the electric field required to reduce the polarization to zero.

Permittivity and impermittivity – Permittivity relates change in electric displacement to change in electric field:

$$\varepsilon = \partial D / \partial E$$

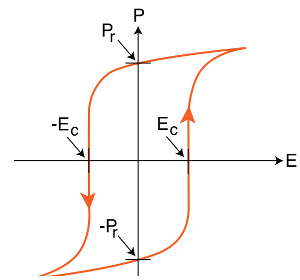


Figure 5: *Ferroelectric hysteresis loop (schematic)*

Permittivity may be considered to be scalar if the medium is isotropic, but in general is a second rank tensor. Impermittivity is the inverse of the permittivity matrix:

$$\{\beta_{mn}\} = \{\varepsilon_{mn}\}^{-1}$$

For piezoelectric crystal classes other than triclinic or monoclinic this simplifies to:

$$\beta_{mn} = 1/\varepsilon_{mn}$$

Relative dielectric constant – The ratio of the permittivity of the material to the permittivity of free space.

$$K = \varepsilon/\varepsilon_0$$

The dielectric constants of various electroded ceramic types are given in Table 4.

Capacitance – Capacitance is the ratio of the change in electric charge on a capacitor electrode to the change in applied electric potential difference between the electrodes:

$$C = \partial q / \partial V$$

The capacitances of various electroded ceramic shapes are given in the Configuration Selection section, page 12.

Electrical Boundary Conditions

Constant E (short circuit) – A constant electric field boundary condition may be satisfied by a short circuit that assures equal electric potential on the piezoceramic boundaries.

Constant D (open circuit) – A constant electric displacement boundary condition may be satisfied by an open circuit that assures that the free electric charge is held constant.

Mechanical

Elastic constants

The elastic compliance matrix relates change in strain to change in stress:

$$s = \partial S/\partial T$$

The elastic stiffness matrix relates change in stress to change in strain and is given by the inverse of the compliance matrix:

$$c = \partial T/\partial S = s^{-1}$$

It can be shown that the inverse of the compliance matrix is not equivalent to a matrix of inverse elements; that is,

$$(s_{ij})^{-1} \neq (s_{ij}^{-1})$$

Poisson's ratio – A ratio of the relative transverse strain to axial strain when a material is stretched axially:

$$\sigma^p = -s^E_{21}/s^E_{11}$$

For most PZT, Poisson's ratio is about 0.31.

Quality Factor Qm – The mechanical quality factor can be defined as a dimensionless measure of dissipation given by:

$$Q_m = (L_1/C_1)^{½} / R_1$$

Where L_1, C_1, and R_1 form the motional branch of the equivalent circuit (Figure 6).

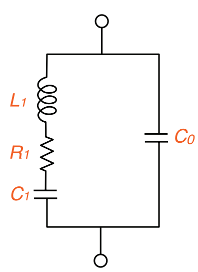


Figure 6: *Equivalent Circuit*

The quality factor may be written in terms of series- and parallel-resonance frequencies as:

$$Q_m = f_p^2/[2\pi f_s |Z_m| C^T (f_p^2 - f_s^2)]$$

Alternatively, Q_m may be expressed as:

$$Q_m = f_0/(f_2 - f_1)$$

Where f_0 is the frequency of maximum amplitude, and f_1 and f_2 are the frequencies at which the amplitude is reduced by 3 dB defining the full-width half-power bandwidth. This is equivalent to the number of radians required for the energy to decay by e^{-1}.

Mechanical Boundary Conditions

Constant S – The strain (ratio of the change in length to length) is held constant.

Constant T – The stress (ratio of applied force to the cross sectional area) is held constant.

Electromechanical

Electrostriction – Electrostriction is a change in dimension resulting from an applied electric field. For non-piezoelectrics, the strain is usually small and proportional to the square of the electric field. All insulating materials are electrostrictive.

Piezoelectricity – A piezoelectric crystal is a crystal that becomes polarized when stress is applied. The polarization is proportional to the applied stress.

Pyroelectricity – Crystals having a spontaneous polarization are pyroelectric. A pyroelectric crystal changes polarization when its temperature changes.

Ferroelectricity – A ferroelectric crystal is a pyroelectric crystal with reversible polarization. Ferroelectrics display the piezoelectric effect as a change in polarization when stress is applied.

Piezoelectric Constants

d – This piezoelectric constant is the ratio of mechanical strain to applied electric field at constant stress (Units: m/V). Conversely, it is the ratio of electric displacement to mechanical stress at constant electric field (Units: C/N):

$$d = (\partial S/\partial E)_T = (\partial D/\partial T)_E$$

g – This piezoelectric constant is the ratio of electric field to applied mechanical stress at constant electric displacement (Units: Vm/N). Conversely, it is the ratio of mechanical strain to electric displacement at constant stress (Units: m^2/C):

$$g = (-\partial E/\partial T)_D = (\partial S/\partial D)_T$$

e – This piezoelectric constant is the ratio of mechanical stress to applied electric field at constant strain (Units: N/Vm). Conversely, it is the ratio of electric displacement to mechanical strain at constant electric field (Units: C/m^2):

$$e = (-\partial T/\partial E)_S = (\partial D/\partial S)_E$$

h – This piezoelectric constant is the ratio of mechanical stress to applied electric displacement at constant strain (Units: N/C). Conversely, it is the ratio of electric field to mechanical strain at constant electric displacement (Units: V/m):

$$h = (-\partial T/\partial D)_S = (-\partial E/\partial S)_D$$

Coupling

Material coupling factors (static or quasi-static)

The material coupling factor is a dimensionless number related to conversion of energy from a mechanical source to electrical work, or vice versa, over an idealized work cycle.

Some of the more useful material coupling factors are given in Table 4 pgs 16-17. Relationships between the material coupling factors and other piezoelectric properties are given in Append-ix II.

The (static) material coupling factors can be related to series- and parallel-resonance frequencies (dynamic behavior) of various specific modes and shapes (Table 1).

Effective coupling factor (dynamic) – The effective coupling factor, keff, is defined by:

$$k_{eff}^{2} = (f_p^2 - f_s^2) / f_p^2$$

It may be used to characterize the separation between the series- and parallel-resonance frequencies of an arbitrary resonator in the absence of intermode coupling. The effective coupling factor is equal to the material coupling factor for the breathing-mode sphere and the hoop mode ring as in these cases all of the elastic energy is dielectrically coupled. For standing wave modes, keff is usually lower than the material coupling factor.

Frequency constants – Frequency constants are defined as the resonance frequency (fs) times the controlling dimension (Table 2).

Frequency constants may be derived from electric, mechanical, and piezoelectric constants or vice versa (See Appendix II).

Dissipation

Dissipation can be represented through the use of complex material properties. For example, complex permittivity may be written as:

$$\varepsilon = \varepsilon' - j\, \varepsilon''$$

A dissipation factor, or loss tangent, is defined by the ratio of imaginary to real components:

$$\tan \delta_{elec} = \varepsilon'' / \varepsilon' \text{ or } \beta'' / \beta'$$

In a similar manner, loss may be included in mechanical and piezoelectric properties:

$$\tan \delta_{mech} = s'' / s' \text{ or } c'' / c'$$

$$\tan \delta_{piezo} = d'' / d',\ g'' / g',\ e'' / e' \text{ or } h'' / h'$$

Thermal

Curie temperature – This is the temperature above which the crystal structure changes to a symmetrical, non-piezoelectric form. The dielectric constant peaks and the net polarization completely disappears at the Curie temperature.

Mass-specific heat capacity – The heat per unit mass required to raise the temperature of a material by one degree. The mass-specific heat of PZT is approximately 420 J/kg-K.

Thermal conductivity – Thermal conductivity is equal to heat flux per unit temperature gradient. The thermal conductivity of PZT is approximately 1.2 W/m-K.

Material Coupling Factor	Shape
$k_{31}^2 = A / (1+A)$ or $k_{31}^2 / (1-k_{31}^2) = A$ where $A = (\pi/2)(f_p/f_s) \tan[(\pi/2)(f_p-f_s)/f_s]$	side electroded bar
$k_p^2 = (f_p^2 - f_s^2)/f_p^2$	thin-wall sphere, breathing mode
$k_{33}^2 = (\pi/2)(f_s/f_p) \tan[(\pi/2)(f_p-f_s)/f_p]$	end electroded rod
$k_t^2 = (\pi/2)(f_s/f_p) \tan[(\pi/2)(f_p-f_s)/f_p]$	disc or plate, 33 thickness

Table 1: Material Coupling Factor

$N_c = f_s \cdot$ mean diameter	Short, thin-walled, radially poled cylinder, 31-hoop mode
$N_p = f_s \cdot$ diameter	Disk, lowest planar mode
$N_{sp} = f_s \cdot$ mean diameter	Thin-walled sphere, breathing mode
$N_t = f_s \cdot$ thickness	Disk or plate, lowest 33-thickness mode
$N_{31} = f_s \cdot$ length	Rod or bar, lowest 31-extensional mode
$N_{33} = f_s \cdot$ length	Rod or bar, lowest 33-extensional mode
$N_{15} = f_s \cdot$ thickness	Plate, lowest 15-thickness shear mode

Table 2: Frequency Constants

K^T_1

- T – Indicates that all stresses on material are constant–for example: zero external forces
- 1 – Indicates that electrodes are perpendicular to 1 axis
- Relative dielectric constant = $\frac{\varepsilon_1^T}{\varepsilon_0}$

K^S_3

- S – Indicates that all strains in material are constant–for example: material completely blocked preventing deformation in any direction
- 3 – Indicates that electrodes are perpendicular to 3 axis
- Relative dielectric constant = $\frac{\varepsilon_3^S}{\varepsilon_0}$

k_{15}

- 15 – Indicates that stress or strain is in shear form around 2 axis
- Indicates that electrodes are perpendicular to 1 axis
- Electromechanical coupling

k_p

- p – This subscript is used only for ceramics. Indicates electrodes perpendicular to 3 axis, and stress or strain equal in all directions perpendicular to 3 axis
- Electromechanical coupling

d_{33}

- Indicates that electrodes are perpendicular to 3 axis
- 33 – Indicates that the piezoelectricity induced strain, or the applied stress, is in direction 3
- $\frac{\text{strain}}{\text{applied field}} = \frac{\text{short circuit charge/ electrode area}}{\text{applied stress}}$

(All stresses, other than the stress involved in second subscript, are constant)

d_h

- h – Indicates that stress is applied equally in 1, 2 and 3 directions (hydrostatic stress); and that electrodes are perpendicular to 3 axis for ceramics
- $\frac{\text{short circuit charge/electrode area}}{\text{applied stress}}$

g_{31}

- Indicates that electrodes are perpendicular to 3 axis
- 31 – Indicates that applied stress, or piezoelectrically induced strain is in direction 1
- $\frac{\text{-field}}{\text{applied stress}} = \frac{\text{strain}}{\text{applied charge electrode area}}$

g_{15}

- Indicates that electrodes are perpendicular to 1 axis
- 15 – Indicates that applied stress, or piezoelectrically induced strain is in shear form around 2 axis
- $\frac{\text{-field}}{\text{applied stress}} = \frac{\text{strain}}{\text{applied charge electrode area}}$

(All stresses, other than the stress involved in second subscript, are constant)

c^D_{11}

- D – Indicates that stiffness is measured with electrode circuit open
- 11 – Indicates that strain is in direction 1
- Indicates that stress is in direction 1
- Stiffness = $\frac{\text{Stress}}{\text{Strain}}$

s^E_{36}

- E – Indicates that compliance is measured with electrodes connected together
- 36 – Indicates that stress is in shear form around 3 axis
- Indicates that strain is in direction 3
- Compliance = $\frac{\text{Strain}}{\text{Stress}}$

(All stresses, other than the stress involved in one subscript, are constant)

Table 3: Typical Piezoelectric Subscripts

BASIC CONFIGURATION SELECTION AND CALCULATIONS

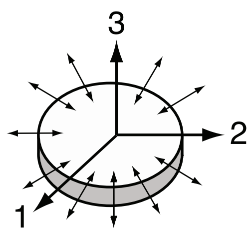
Configurations are normally selected to produce the desired actuation or sensing vibrational mode. Typically, the controlling dimension is chosen to a specific resonance frequency of interest. Other dimensions are chosen to minimize other vibrational modes near the frequency of interest, to a specific aperture size, or to accommodate the desired actuation or sensing area. The volume of the piezoelectric ceramic required may also be driven by the temperature, stress, field and power distribution discussed on page 26.

The piezoelectric industry uses the orthogonal axis originally assigned by crystallographers to determine the mode of operation. That is: 1 corresponds to the x axis, 2 corresponds to the y axis and 3 corresponds to the z axis. The direction of polarization is defined as the 3 axis.

Note: For the following equations, all variables use SI units.

Modes Of Vibration Of The Piezoelectric Resonator

Thin disc
Radial Mode



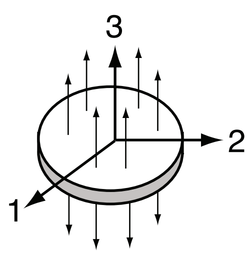
Electroded on flat surfaces.
Poled through thickness.

$$C^T = \frac{\pi K_3^T \varepsilon_0 (Diameter)^2}{4t}$$

$$K_3^T = \frac{4C^T t}{\pi \varepsilon_0 (Diameter)^2}$$

Frequency constant $N_p = f_s \cdot diameter$

Thin Disc or Plate
Thickness Mode



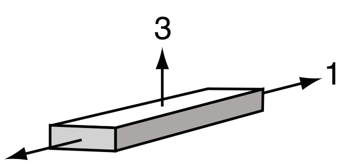
Electroded on flat surfaces.
Poled through thickness.

$$C^T = \frac{\pi K_3^T \varepsilon_0 (Diameter)^2}{4t}$$

$$K_3^T = \frac{4C^T t}{\pi \varepsilon_0 (Diameter)^2}$$

Frequency constant $N_t = f_s \cdot t$

Long Thin Bar Length
Extensional Mode



Electroded on shaded surfaces.
Poled through thickness.

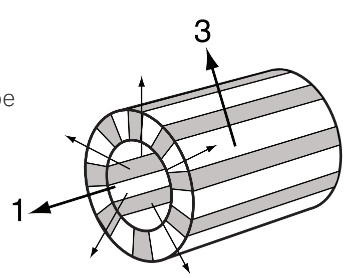
$$C^T = \frac{K_3^T \varepsilon_0 (Electrode\ Area)}{t}$$

$$K_3^T = \frac{C^T t}{\varepsilon_0 (Electrode\ Area)}$$

Frequency constant $N_{31} = f_s \cdot \ell$

Striped Thin Wall Tube

33-Hoop Mode



Electroded on shaded stripes.
Poled between stripes.

$$C^T = \frac{0.8 K_3^T \varepsilon_0 n\, l\, (wall\ t)}{(L_3)}$$

$$K_3^T = \frac{C^T (L_3)}{0.8\, \varepsilon_0\, n\, l\, (wall\ t)}$$

$$f_s \approx \frac{L_0 + L_3}{2 \pi a \left[\left(s_{03} L_0 + s_{33}^E L_3\right)\left(\rho_0 L_0 + \rho_3 L_3\right) \right]^{1/2}}$$

n = number of stripes

L_0 = avg. width of electrode stripe

L_3 = avg. space between stripes

mean radius $a = \frac{n (L_0 + L_3)}{2\pi}$

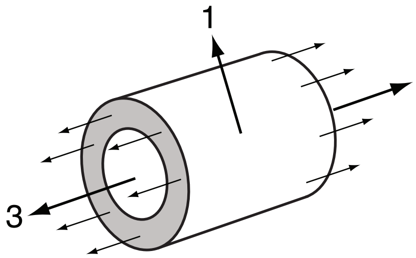
s_{03} = compliance of unpoled ceramic under stripe

s_{33}^E = compliance of poled ceramic under stripe

ρ_0 = density of unpoled ceramic under stripe

ρ_3 = density of poled ceramic under stripe

Thin Wall Tube
Length Mode

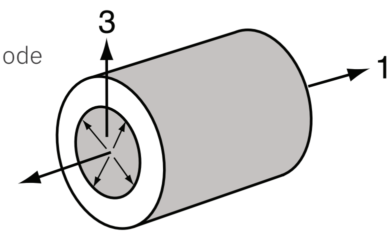


Electroded on end (flats).
Poled through length.

$$C^T = \frac{\pi K_3^T \varepsilon_0 \left(OD^2 - ID^2\right)}{4l}$$

Frequency constant $N_{33} = f_s \cdot \ell$

Thin Wall Tube
Circumferential Mode



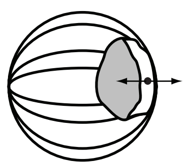
Electroded on OD & ID.
Poled through wall thickness.

$$C^T = \frac{2\pi K_3^T \varepsilon_0 l}{\ln\left(\frac{OD}{ID}\right)}$$

$$K_3^T = \frac{C^T \ln\left(\frac{OD}{ID}\right)}{2\pi \varepsilon_0 l}$$

Frequency constant $N_c = f_s \cdot \textit{mean diameter}$

Thin Wall Sphere
Radial Mode



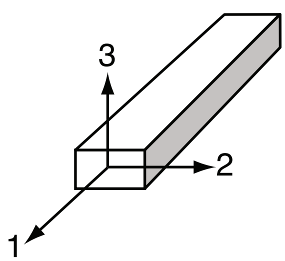
Electroded on curved
surfaces. Poled
through wall thickness

$$C^T = \frac{\pi K_3^T \varepsilon_0 (OD \cdot ID)}{(wall\ t)}$$

$$K_3^T = \frac{C^T (wall\ t)}{\pi \varepsilon_0 (OD \cdot ID)}$$

Frequency constant $N_{sp} = f_s \cdot \textit{mean diameter}$

Shear Mode



Electroded on shaded
surfaces (90° to polarize).
Poled through length (3 axis).

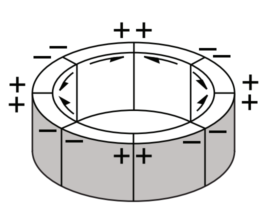
$$C^T = \frac{K_1^T \varepsilon_0 (Electrode\ Area)}{t}$$

$$K_1^T = \frac{C^T t}{\varepsilon_0 (Electrode\ Area)}$$

Frequency constant $N_{15} = f_s \cdot t \textit{ (1 axis)}$

Segmented Cylinder
containing all active
material

33-Hoop Mode



$$f_s \approx \frac{1}{2\pi a \left(s_{33}^E \rho\right)^{1/2}} \quad *$$

s_{33}^E = *short circuit elastic compliance*

ρ = *density of ceramic*

a = *mean radius*

** Actual performance will depend on joints*

MATERIAL SELECTION

"Hard" Piezoelectric Materials

"Hard" piezoelectric materials are those materials whose properties are stable with temperature, electric field, and stress. Stability is achieved by chemical composition to pin or restrict domain wall motion or reduce extrinsic contribution to the piezoelectric effect. They are used in applications requiring high power actuation or projection. The applications often have a narrow bandwidth, but are usually operated either at resonance or well under resonance. Some typical applications for these "hard" piezoelectric materials are shown in Figure 7.

"Soft" Piezoelectric Materials

"Soft" piezoelectric materials are those materials whose properties have been enhanced for sensing, actuation, or both. They have high coupling and high permittivity. Property enhancement was made at the expense of temperature, electric field, and stress stability. Property enhancement is achieved by chemical composition to allow domain wall motion to extrinsically contribute to the piezoelectric effect. Some typical applications for these "soft" piezoelectric materials are shown in Figure 7.

	GENERAL SELECTION CRITERIA FOR "HARD" PZT				GENERAL SELECTION CRITERIA FOR "SOFT"		
	EC-69	EC-67	EC-63	EC-64	EC-65	EC-66	EC-70
Low Power Sonar	X	X		X	X	X	X
High Power Sonar	X	X					
Receivers	X	X		X	X	X	
Transducers	X	X		X			
Accelerometers				X	X	X	
Actuators	X	X		X	X	X	
NTD	X	X		X	X	X	X
Pressure	X	X		X	X	X	
Flow Meters	X	X		X	X	X	
Medical Diagnostics				X	X	X	
Medical Therapeutic	X	X		X			
Gas Ignitors					X	X	
Ultrasonic Cleaners	X	X	X	X			
Ultrasonic Welders	X	X	X	X			
Motors	X	X		X			
Audible Alarms					X	X	X

Figure 7: *Selection criteria for piezoelectric materials*

MATERIAL SELECTION

L3Harris manufactures a wide range of piezoelectric materials including lead zirconate titanate (PZT) materials, lead titanate (PT) materials and a piezoelectric lead magnesium niobate material (PMN).

Each material type has a modified chemical composition and optimized manufacturing process in order to tailor the material to specific applications. L3Harris offers materials which meet the DoD-1376B(sh) material specification, as noted.

Description of L3Harris Materials

EC-63

This "hard" lead zirconate titanate material was developed for moderate power applications. It features low loss tangent, high piezoelectric charge constant and high Curie temperature. These features make this material suitable for ultrasonic cleaning and other acoustic projector applications.

EC-64* (Navy Type I)

This "hard" lead zirconate titanate material was developed for general power applications. Having high electromechanical coupling, high piezoelectric charge constant, and low dielectric loss under high electric driving fields, it is suitable for high power, low frequency broad band projectors, squeeze sensors, spark generators, and other high power electro-acoustic devices.

EC-65* (Navy Type II)

This "soft" lead zirconate titanate material was developed for highest sensitivity sensors, hydrophones, accelerometers, and impact sensors or spark generators. It features high dielectric constant, the highest piezoelectric voltage constant and high Curie temperature.

EC-66

This "soft" lead zirconate titanate material was developed for specialty receivers and sensors requiring a higher charge output or capacitance than EC-65 material could provide.

EC-67

This "hard" lead zirconate titanate material is a modified version of EC-69 material featuring higher electromechanical coupling for broadband high power projector applications, such as low frequency flextensional projectors.

EC-69* (Navy Type III)

This "hard" lead zirconate titanate material provides the maximum stability under temperature, electric field, and stress. It was designed for high power acoustic projectors, ultrasonic welders, bonders, hand-held medical, dental devices, and deep water applications.

EC-70* (Navy Type V)

This "soft" lead zirconate titanate material provides high dielectric constant, high piezoelectric charge and voltage constants. It was designed for sensor applications requiring high energy output (both voltage and current). It is used in special fuse, accelerometer, and hydrophone applications.

EC-76* (Navy Type VI)

This "soft" lead zirconate titanate material provides the highest dielectric constant and piezoelectric charge constant. It was designed for low power high displacement actuator or positioning applications. It has the lowest operational temperature range, temperature, electric field and stress stability of all the lead zirconate titanate materials.

EC-97

This lead titanate material features the highest piezoelectric voltage constant and highest cross-coupling mode cancellation. It was designed for single mode or hydrostatic applications, such as non-destructive testing, accelerometers, and hydrophones.

EC-98

This lead magnesium niobate material is a piezoelectric material with a high dielectric constant and a high piezoelectric charge constant in exchange for lower operational temperature range and stability. It was designed for high displacement actuators, micro-positioners, and high frequency medical ultrasonic imaging applications.

**Note: DOD-STD-1376A(SH) Ceramic Types I-VI*

Description of L3Harris Materials

MATERIALS		LEAD TITANATE	LEAD MAGNESIUM NIOBATE PMN	LEAD ZIRCONATE TITANATE "SOFT"				LEAD ZIRCONATE TITANATE "HARD"			
ElectroMechanical Properties		**EC-97**	**EC-98**	**EC-65**	**EC-66**	**EC-70**	**EC-76**	**EC-63**	**EC-64**	**EC-67**	**EC-69**
Physical Properties	Density (x 10^3Kg/m^3)	6.7	7.85	7.5	7.45	7.45	7.45	7.5	7.5	7.5	7.5
	Young's Modulus (x 10^{10}N/m^2)	12.8	6.1	6.6	6.2	6.3	6.4	8.9	7.8	9.3	9.9
	Curie Temperature (°C)	240	170	350	270	220	190	320	320	300	300
	Mechanical Q for a thin disc	950	70	100	80	75	65	500	400	900	900
Electric Properties at 25°C	Dielectric Constant @ 1 kHz	270	5500	1725	2125	2750	3450	1250	1300	1100	1050
	Dissipation Constant @ 1 kHz (%)	0.9	2.0	2.0	2.0	2.0	2.0	0.4	0.4	0.3	0.3
	k_{31}	0.01	0.35	0.36	0.36	0.37	0.38	0.34	0.35	0.33	0.31
	k_p	0.01	0.61	0.62	0.62	0.63	0.64	0.58	0,60	0.56	0.52
	k_{33}	0.53	0.72	0.72	0.72	0.74	0.75	0.68	0.71	0.66	0.62
	k_{15}	0.35	0.67	0.69	0.68	0.67	0.68	0.69	0.72	0.59	0.55
	d_{31} (x10^{-12} Meter/Volt)	-3.0	-312	-173	-198	-230	-262	-120	-127	-107	-95
	d_{33} (x10^{-12} Meter/Volt)	68.0	730	380	415	490	583	270	295	241	220
	d_{15} (x10^{-12} Meter/Volt)	67.0	825	584	626	670	730	475	506	362	330
	g_{31} (x10^{-3} Volt Meters/Newton)	-1.7	-6.4	-11.5	-10.6	-9.8	-8.6	-10.3	-10.7	-10.9	-10.2
	g_{33} (x10^{-3} Volt Meters/Newton)	32.0	15.6	25.0	23.0	20.9	19.1	24.1	25.0	24.8	23.7
	g_{15} (x10^{-3} Volt Meters/Newton)	33.5	17.0	38.2	36.6	35.0	28.9	37.0	39.8	28.7	28.9
Elastic Constants	$_{11}^{E}$ (x10^{-12}meters^2/Newton)	-	16.3	15.2	16.1	15.9	15.6	11.3	12.8	10.8	10.1
	s_{12}^{E} (x10^{-12}meters^2/Newton)	-	-5.6	-5.3	-5.5	-5.4	-4.7	-3.7	-4.2	-3.6	-3.4
	s_{33}^{E} (x10^{-12}meters^2/Newton)	-	21.1	18.3	17.7	18.0	19.8	14.3	15.0	13.7	13.5
	s_{11}^{D} (x10^{-12}meters^2/Newton)	-1.7	14.3	13.2	14.0	13.7	13.3	10.0	11.2	9.6	9.1
	s_{12}^{D} (x10^{-12}meters^2/Newton)	-	-7.6	-7.3	-7.6	-7.6	-7.0	-5.0	-5.8	-4.8	-4.4
	s_{33}^{D} (x10^{-12}meters^2/Newton)	-	10.2	8.8	8.5	8.1	8.7	7.7	7.4	7.7	8.3

MATERIALS		LEAD TITANATE	LEAD MAGNESIUM NIOBATE PMN	LEAD ZIRCONATE TITANATE "SOFT"				LEAD ZIRCONATE TITANATE "HARD"			
ElectroMechanical Properties		**EC-97**	**EC-98**	**EC-65**	**EC-66**	**EC-70**	**EC-76**	**EC-63**	**EC-64**	**EC-67**	**EC-69**
Frequency Constant (kHz-Meter) or (kHz-Inches) x 39.37	N_{31}=Freq. x Length – Length Mode	2.13	1.385	1.359	1.341	1.321	1.359	1.677	1.642	1.733	1.765
	N_t=Freq. x Thickness – Flat Disc or Plate	2.21	1.803	1.778	1.752	1.727	1.765	2.069	2.026	2.141	2.181
	N_c=Freq. x Mean Diameter Circumferential Mode	1.315	0.835	0.876	0.864	0.851	0.889	1.034	1.012	1.071	1.091
	N_{sp}=Freq. x Mean Diameter – Radial Mode	2.26	1.44	1.473	1.452	1.432	1.473	1.753	1.716	1.809	1.843
	N_{15}=Freq. x Thickness – Shear Mode	1.43	1.09	1.082	1.075	1.058	1.105	1.349	1.321	1.333	1.415
	N_p=Freq. x Diameter – Planar Mode	2.76	1.97	1.994	1.968	1.943	1.981	2.195	2.149	2.269	2.311
Electric Properties at 25°C	Dielectric Constant	-0.3	-1.5	-0.8	-1.5	-2.1	-2.0	- 4.1	-4.2	-3.2	-3.0
	Coupling Constant	-0.4	-0.4	-0.3	-0.04	-0.4	-0.4	-2.1	-2.1	-1.6	-1.4
	Resonant Frequency	0.05	0.4	0.2	0.3	0.4	0.3	1.0	1.0	0.8	0.75
Elastic Constants	Maximum Positive Field (V/mm)	-	900 (DC only)	600	525	450	400	-	700	800	800
	Maximum Negative Field (V/mm)	-	450 (DC only)	300	260	225	200	-	350	400	400
	Applied Field @ 25° C	79	79	79	79	79	79	394	394	394	394
	Dielectric Constant % Increase	1.5	22.5	12.0	12.3	12.6	14.0	18.0	18.0	3.8	3.2
	Dissipation Factor	0.8	6.2	7.3	6.9	7.1	7.9	3.0	3.0	0.9	0.6

Table 4: Piezoelectric Ceramic Electromechanical Properties

The above values are nominal material values. Actual production values can vary ± 10% for electrical properties.

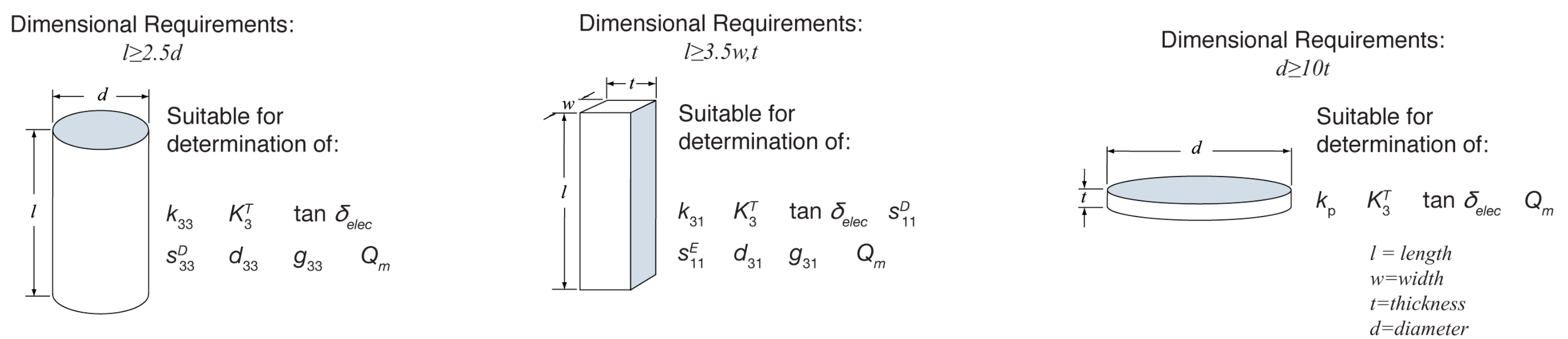


Figure 8: *Suitable Part Configurations needed for the determination of given electrical parameters*

ELECTRICAL CHARACTERISTICS OF A PIEZOELECTRIC ELEMENT

Electrical impedance is defined as the voltage drop across an element divided by the current through the element. For a piezoelectric element, the electrical impedance may exhibit the distinguishing characteristic of one or more resonances that result from coupling between electrical energy input and mechanical motion. Figure 9 illustrates the electrical impedance of a piezoelectric element near an isolated resonance. The impedance of a non-piezoelectric element of similar shape and dielectric properties is also shown. For each mechanical resonance in the piezoelectric element, a resonance/anti-resonance pair will exist in the electrical impedance.

A piezoelectric element's impedance can be modeled by the equivalent circuit shown in Figure 10. Four fundamental parameters, C_1, L_1, R_1 and C_0 define the network completely and are assumed to be constants independent of frequency. In general, the parameters are independent of frequency only for a narrow range of frequencies near the resonance frequency and only if the mode of interest is sufficiently isolated from other modes.

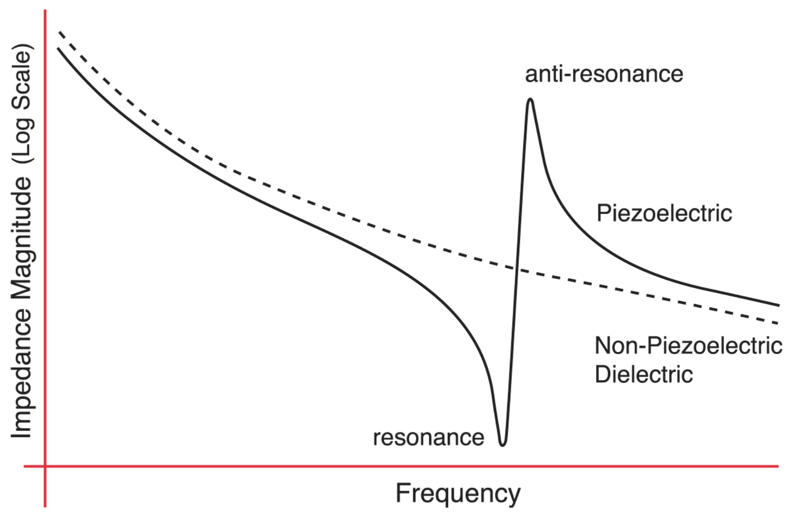


Figure 9: *Impedance versus frequency for dielectric and piezoelectric elements.*

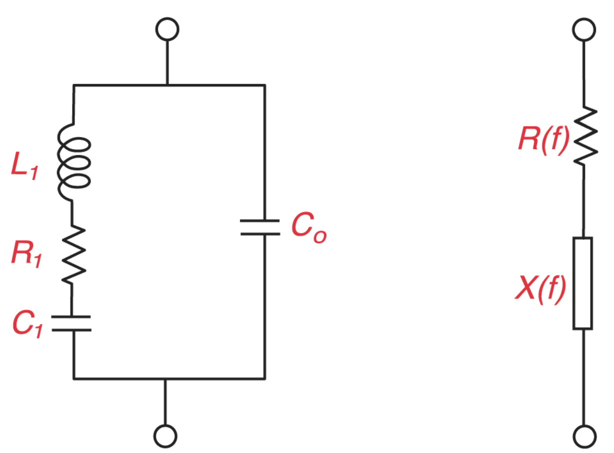


Figure 10: *Equivalent circuit model for a piezoelectric resonance.*

For the purpose of defining the different characteristic frequencies, the impedance magnitude *Z(f)* of the equivalent network, its series resistive component *R(f)*, its series reactive component *X(f)*, and the reactance $X_1(f)$ of the L_1- C_1- R_1 branch are plotted as a function of frequency in Figure 11. These curves are only qualitative in character and do not represent a particular piezoelectric resonator. The idealized admittance circle of a piezoelectric resonator is illustrated in Figure 12.

The construction of test fixtures must be carefully considered to minimize any stray capacitance. The effect of stray capacitance, which appears in parallel to the sample, is to reduce the measured anti-resonant frequency. Because the resonant frequency is virtually unaffected, the result is to make the coupling coefficient appear lower than the actual value.

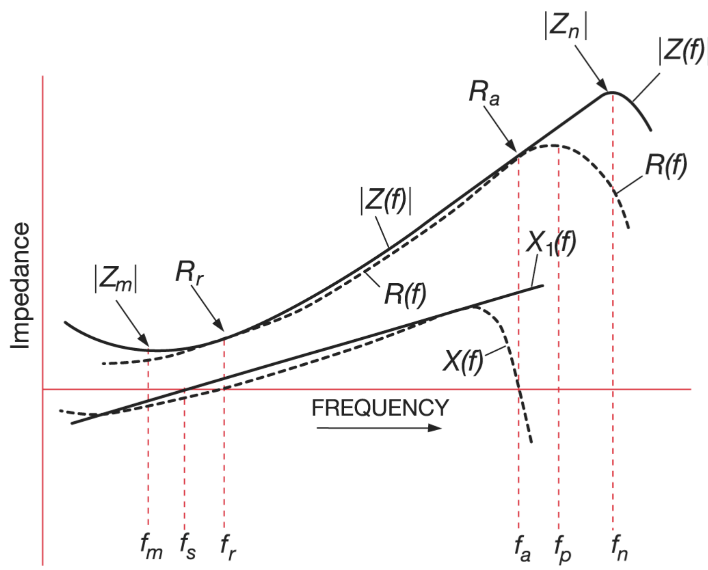


Figure 11

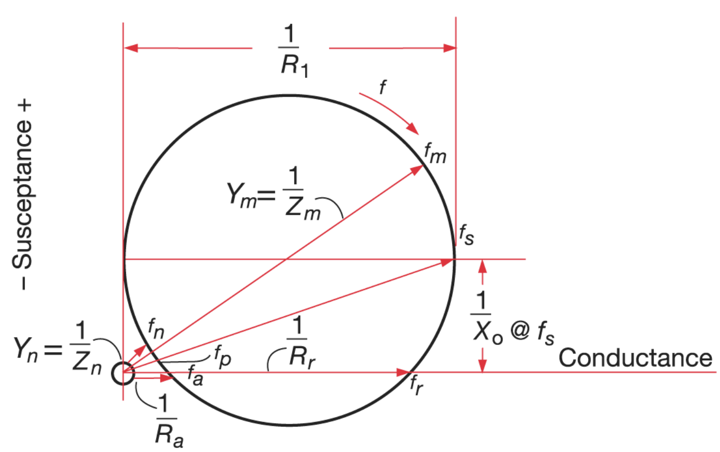


Figure 12

PROPERTIES OF L3HARRIS MATERIALS

Powder Characteristics

L3Harris has the largest piezoelectric powder manufacturing capacity in the US. L3Harris can provide fired components as well as most special material formulations and powder processing development for customers with specific needs per contract. We produce piezoelectric powders utilizing traditional mixing, calcining, and milling ceramic processing techniques. Typically, piezoelectric ceramic powder manufacturing takes 2 to 4 weeks.

L3Harris ceramic powders are free flowing spray dried powders with binder added. They are ready to form by mechanical/hydraulic dry pressing or isostatic pressing methods. Powders can also have a lubricant added for a particular application. For large custom orders, L3Harris can modify standard production powders to meet particular desired properties. The most common modifications are binder type and amount, powder particle size, and dielectric/piezoelectric characteristics. L3Harris has the facilities to provide test data including screen analysis, tap density, angle of repose, particle size distribution, moisture content, loss on ignition (LOI), specific surface area, x-ray diffraction (XRD), and scanning electron microscopy (SEM).

L3Harris goal is to achieve powder, chemical, physical, and electrical properties that meet or exceed customers' needs for their process and product.

Time Stability (Aging)

Aging is a time dependent relaxation of the piezoelectric material and properties, measured logarithmically from the date of the material's polarization. Since all piezoelectric ceramic materials exhibit aging, the dielectric, piezoelectric, and elastic properties must be specified with reference to the time after polarization. For example, the former DoD-1376B(sh) standard referred most dielectric and piezoelectric properties to 10 days after polarization. Since aging is logarithmic, properties become more stable with time. Aging rates are dependent primarily on material type and partially on processing conditions.
The standard aging rate equation is:

$$X_T = X_t + X_t \bullet AR \bullet \log_{10}(T/t),\ (T>t)$$

Where X is the parameter of interest, T is the time of interest (e.g. 10 days), t is the number of days after polarization when the part is measured, and AR is the percent aging rate.

Due to the pinning or restriction of domain wall motion in "hard" piezoelectric ceramic materials and low extrinsic piezoelectric contribution, "hard" piezoelectric materials exhibit large aging rates. Conversely, since "soft" piezoelectric materials have easy domain wall motion, relaxation occurs immediately after polarization. Therefore, "soft" piezoelectric materials aging is low over measurable time periods. Typical measurement time is 1 to 100 days after polarization.

Low Field Properties

All low field properties are measured according to IEEE standard and former DoD-1376B(SH) standards. See Table 3.

Temperature Stability

All piezoelectric ceramics remain active from liquid helium temperatures to the Curie temperature. At liquid helium temperature, properties are low, having only the materials' intrinsic contribution. At higher temperatures, properties increase due to thermally activated extrinsic domain wall motion, which contributes to the dielectric and piezoelectric properties. Materials with lower Curie temperatures have higher extrinsic contribution and therefore greater change in properties with temperature. Due to the change in properties with temperature, dielectric and piezoelectric property values should be referred to a particular temperature, such as a nominal 20°C as stated in the former DoD-1376B(sh) standard. The changes in various properties with temperature for L3Harris materials are shown in Figures 13 through 18.

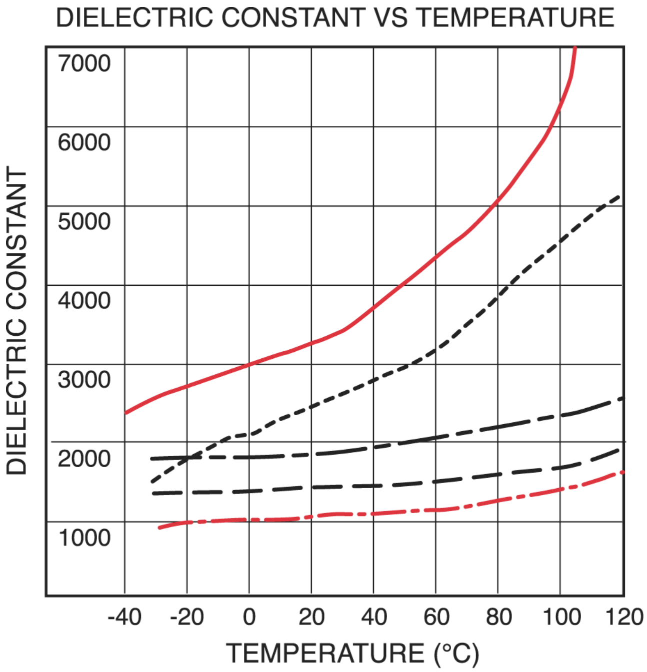


Figure 13: *Dielectric constant* K_3^T *as a function of temperature for Lead Zirconate Titanates.*

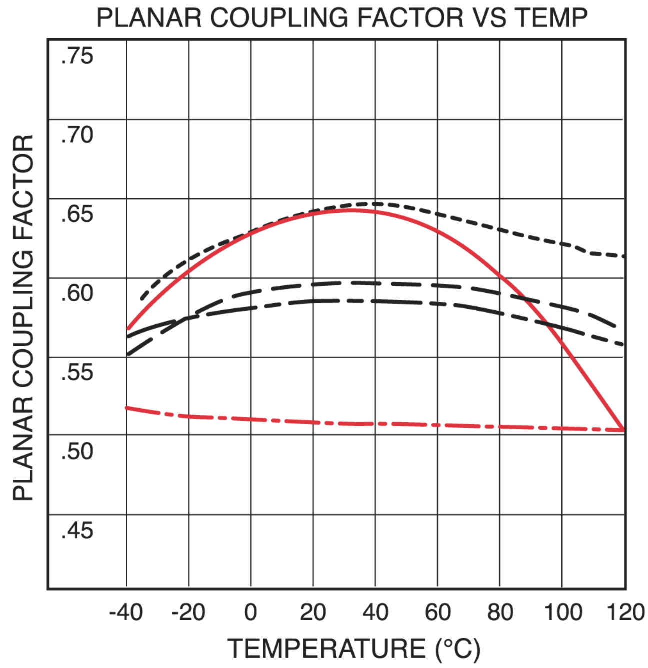


Figure 14: *Planar coupling factor k as a function of temperature for Lead Zirconate Titanates.*

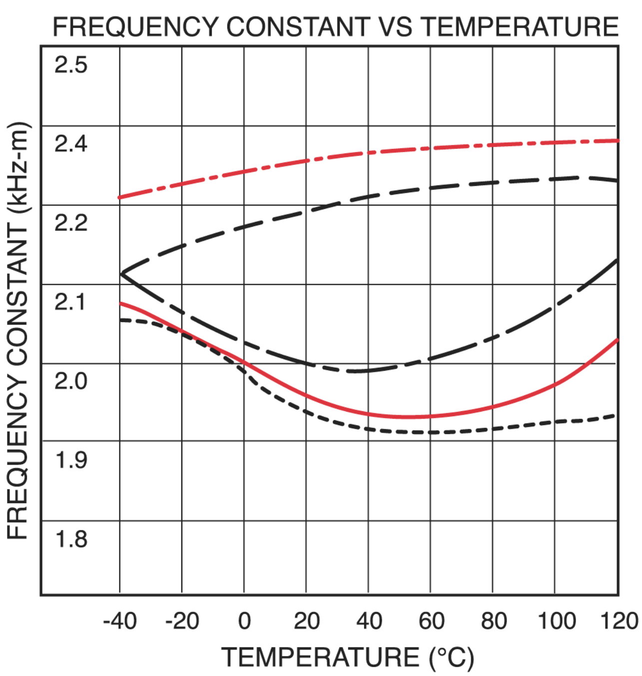


Figure 15: *Planar frequency constant* N_p *as a function of temperature for Lead Zirconate Titanates.*

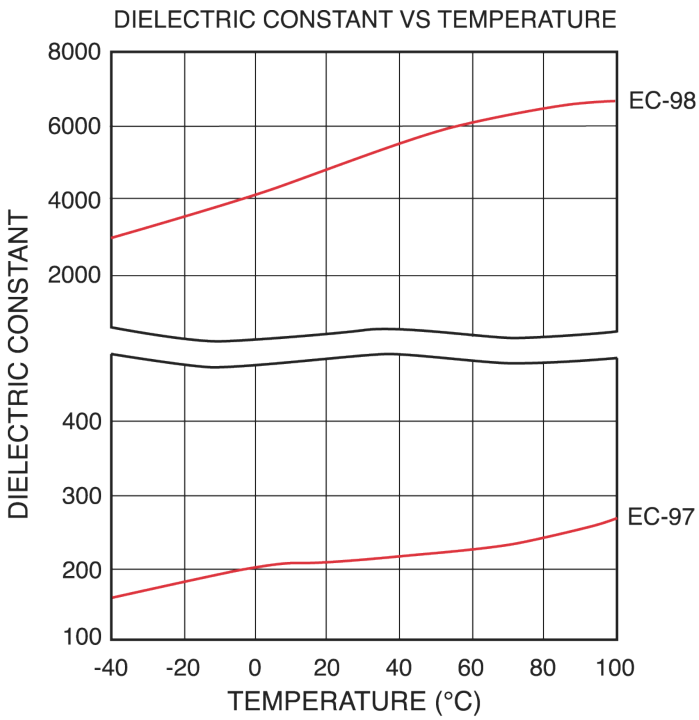


Figure 16: *Dielectric constant K^T as a function of temperature for Lead Titanate, Lead Magnesium Niobate.*

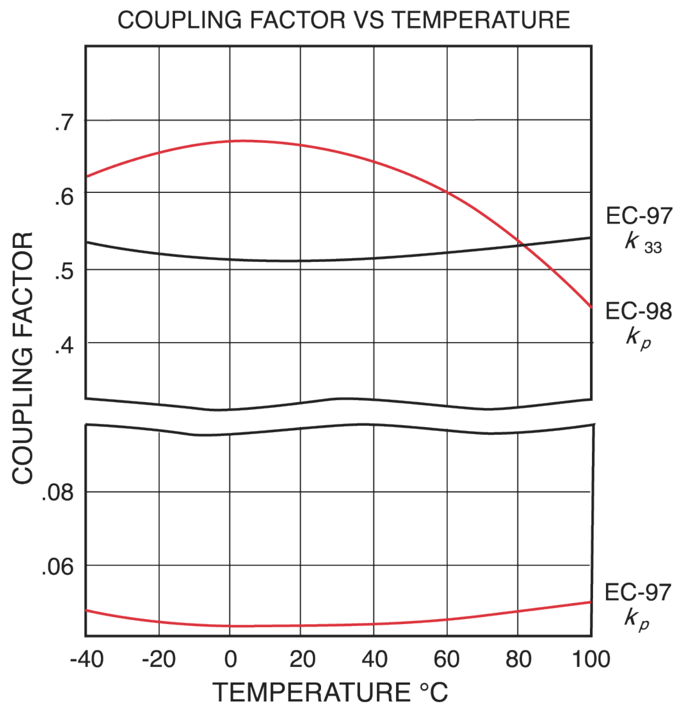


Figure 17: *Planar coupling factor k_p as a function of temperature for Lead Titanate, Lead Magnesium Niobate.*

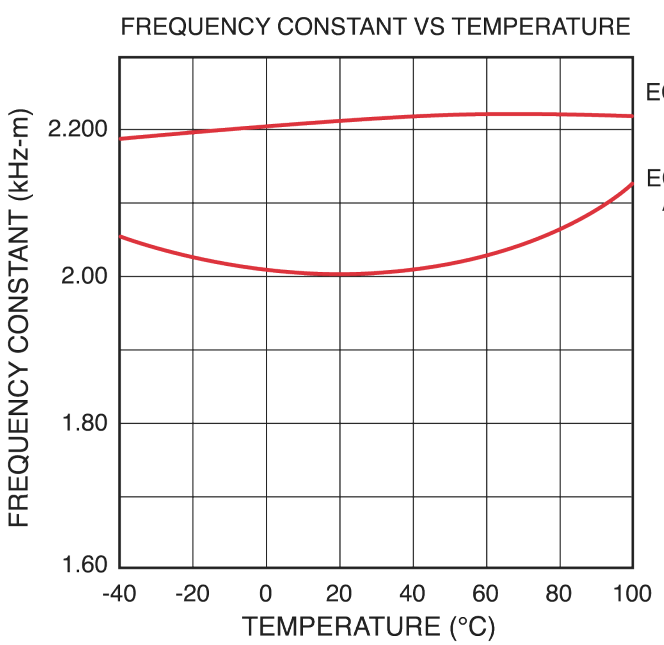


Figure 18: *Thickness frequency constant N_t, as a function of temperature for Lead Titanate, Planar frequency constant N_P as a function of temperature for Lead Magnesium Niobate.*

Coupling Factor Graphs

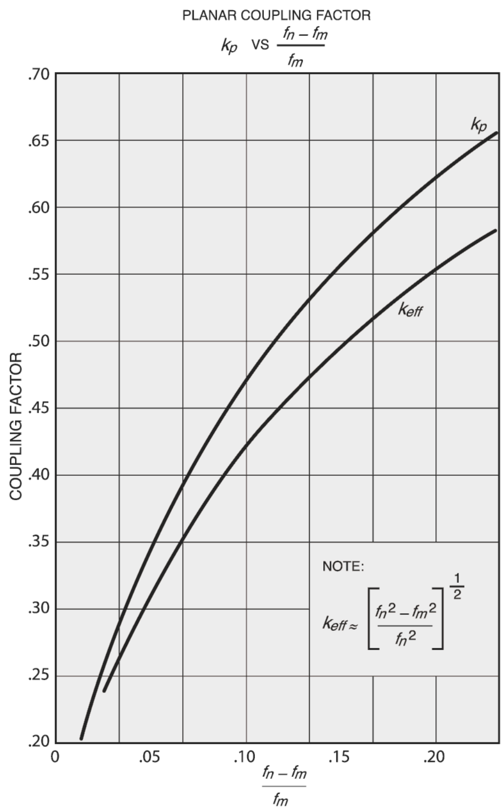


Figure 19: *Planar oupling factor of a Disc, per Figure 8*

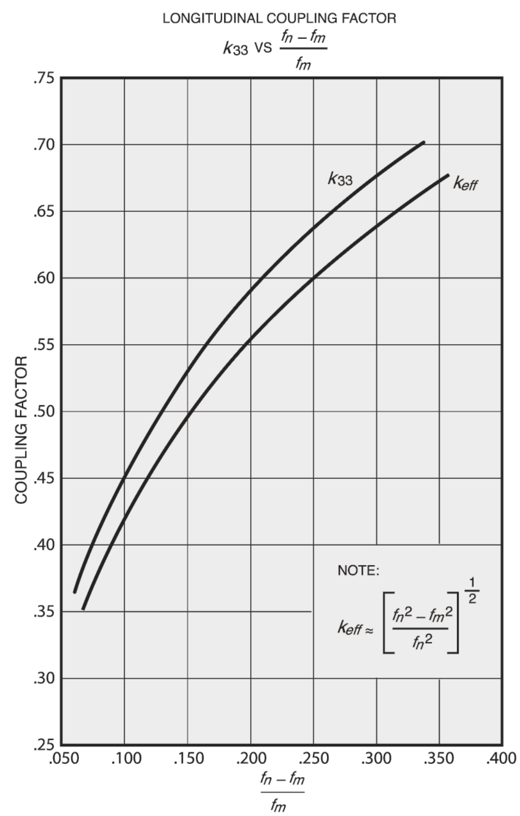


Figure 20: *Longitudinal coupling factor of a Rod, per Figure 8*

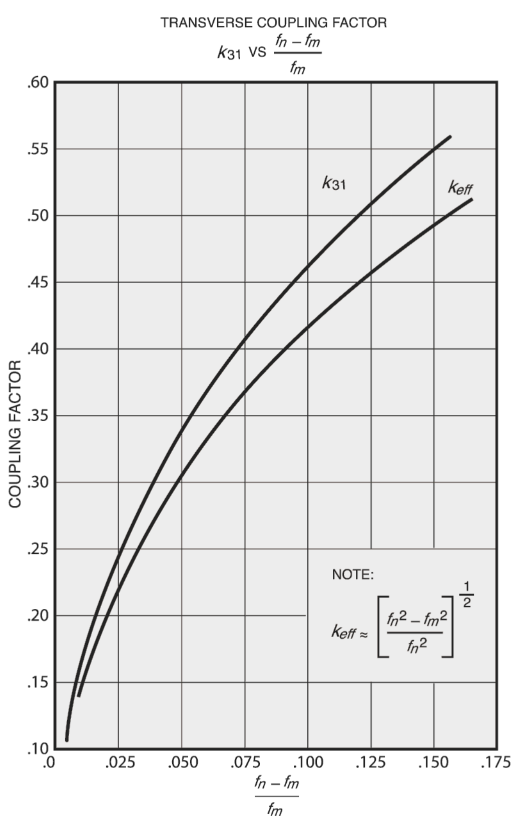


Figure 21: *Transverse coupling factor of a Bar, per Figure 8*

STRESS OR PRESSURE STABILITY

Dielectric and piezoelectric properties of piezoelectric ceramics are dependent on stress or pressure due to extrinsic contribution of domain wall motion. As such, "hard" piezoelectric materials are more stable than "soft" piezoelectric materials. The effects of stress, dynamic or static, on dielectric and piezoelectric properties of PZT are complex. An increase in static planar stress $(T_1=T_2)$ will cause K^T_{33} to decrease with little change in g_{31}. An increase in hydrostatic pressure will cause K^T_{33} to increase with little change to g_h. For hard PZT a static, compressive, unidirectional stress parallel to the polar axis (T_3) will cause K^T_{33} to increase and g_{33} to slightly decrease. For soft PZT, the decrease in g_{33} will be much greater. For dynamic stress, Figure 22 illustrates the changes in Young's Modulus and mechanical quality factor.

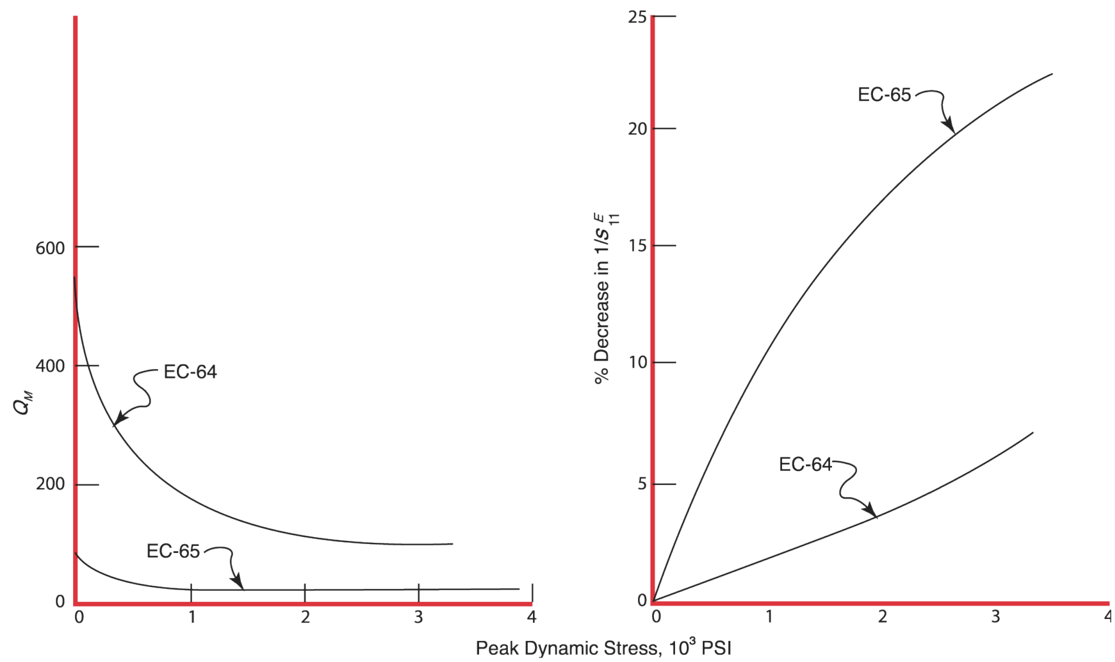


Figure 22: *Mechanical quality factor QM and Young's Modulus ($1/s^E_{11}$) as a function of peak dynamic stress perpendicular to the polar axis*

ELECTRIC FIELD STABILITY

Dielectric and piezoelectric properties of piezoelectric ceramics are highly dependent on electric field due to extrinsic contribution of domain wall motion. As such, "hard" piezoelectric materials are more stable than "soft" piezoelectric materials. The changes in dielectric constant and dissipation factor at high electric field for various L3Harris piezoelectric ceramics are shown in Figures 23 - 26.

HIGH FIELD CAPABILITIES OF LEAD ZIRCONATE TITANATE

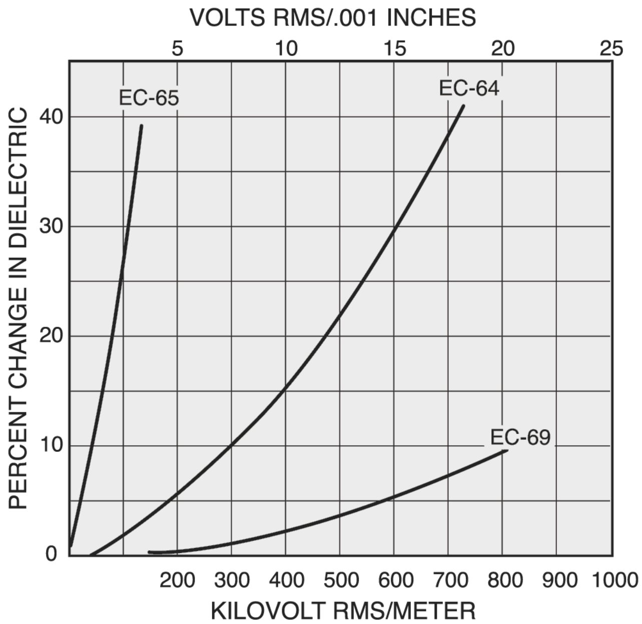


Figure 23

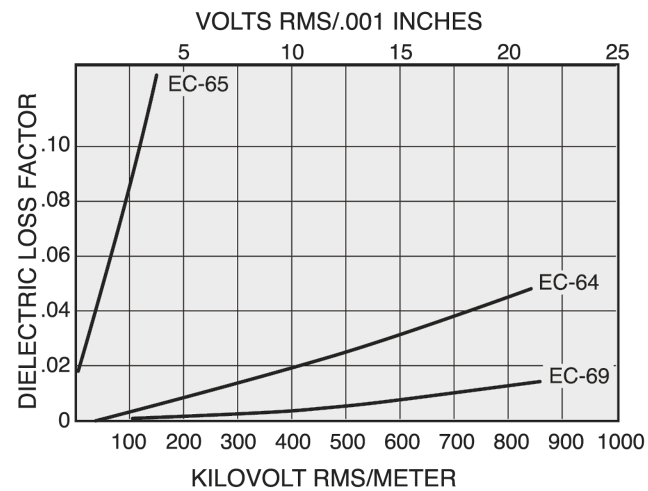


Figure 24

HIGH FIELD CAPABILITIES OF LEAD TITANATE

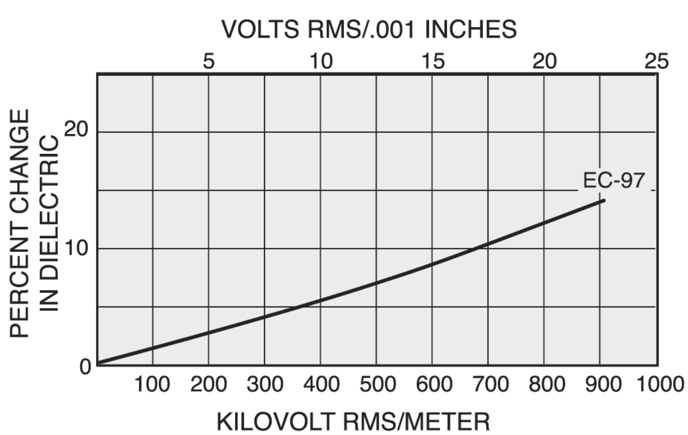


Figure 25

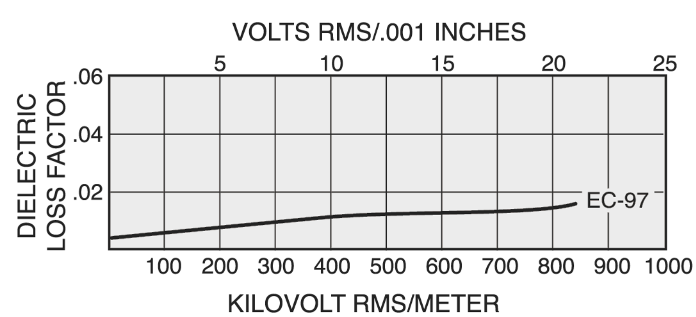


Figure 26

LIMITATIONS

Piezoelectric Material Limitations

Limitations for piezoceramics are difficult to define due to the tremendous range of applications requirements and operational environments. Piezoelectric ceramic may be damaged by excessive temperature, mechanical stress, or electric field. Temperature, mechanical stress, and electric field may combine to cause damage that would not have resulted from a single stressor, and so it is important to take all of these factors into consideration when specifying a piezoelectric ceramic type. These stressors may also affect the ageing rates of the ceramic.

Temperature Limitations

Most piezoelectric ceramics start to depolarize at approximately half the Curie Temperature in degrees Celsius. The dielectric constant peaks, and the net polarization completely disappears at the Curie Temperature. The Curie Temperatures given in Table 4 do not include effects of mechanical or electrical bias and were measured under low voltage conditions. The temperature limitation would increase with a positive DC bias and would decrease with a high AC field, compressive mechanical bias, or high mechanical loading.

Mechanical Stress Limitations

As with all ceramics, piezoelectric ceramics are brittle and have a much higher compressive strength than tensile strength. Many piezoelectric transducers are therefore operated under a compressive bias, particularly for high power applications. High mechanical stress may cause depolarization of the ceramic long before the compressive mechanical strength limit is reached. The strength and toughness of the material are highly dependent on its processing conditions. Smaller grain size is associated with greater fracture toughness[1,2]. Mechanical strength becomes anisotropic after the ceramic is electrically poled[2,3]. Cracks in unpoled PZT and PMN ceramic have been observed to propagate more readily in a direction perpendicular to an applied electric field[4].

For high hydrostatic pressure, high stress, or squeeze ignition applications, hard piezoelectric materials are suitable. In high dynamic stress applications, such as impact ignition, soft piezoelectric materials may be suitable.

Electric Field Limitations

Piezoelectric ceramics become active by polarizing the material with a high positive DC voltage. As such, they have been prescreened for dielectric failure. Piezoelectric ceramics may be partially or entirely depolarized with the application of a high negative electric field. A positive DC bias may be applied in applications that are limited by the negative voltage swing. The Coercive field, E_c, of hard piezoelectrics is greater than 10 kV/cm; E_c of soft piezoelectrics is between 1 kV/cm and 10 kV/cm; and E_c of electrostrictors is less than 1 kV/cm. Recommended electric field limits are provided in Table 3. The given limits do not consider compressive mechanical bias or temperature.

Transducer Power Limitations

A transducer's ability to meet power output requirements may be limited by dynamic strength, temperature rise, or efficiency. Dynamic strength is usually a limitation only when the transducer has high Q_m and the ceramic is not under compressive mechanical bias. Dielectric, elastic (mechanical), and piezoelectric losses in the ceramic as well as other mechanical losses contribute to temperature rise and inefficiency. Piezoelectric transducers tend to be efficiency limited when operated at low duty cycle and temperature limited when used in continuous operation. For temperature limited transducers, removal of heat is as important as minimizing the generation of heat. Dielectric losses increase as temperature rises. The positive feedback between loss and temperature can result in "thermal runaway" and transducer failure. As ceramic losses at high drive result largely from ceramic domain wall motion, hard ferroelectric ceramics such as EC-69, 67, 64, or 63 materials are indicated for high output power applications.

References

[1] *K. Uchino and T. Takasu, Inspec 10, 29 (1986).*

[2] *K. Uchino and J.R. Giniewicz, Micromechatronics, Marcel Dekker, Inc., 156 – 157, 2003. ISBN: 0-8247-4109-9.*

[3] *T. Yamamoto, H. Igarashi and K.Okazaki, Ferroelectrics 50, 273 (1983).*

[4] *H. Wang and R.N. Singh, Ferroelectrics 168, 281 (1995).*

BASIC PIEZOELECTRIC CERAMIC APPLICATIONS

Applications

Four alternate forms of constitutive equation pairs (see Appendix I), each with its related piezoelectric constant, are all equivalent. The choice of which to use is typically dictated by geometrical, mechanical, and electrical circumstances that allow certain variables to be approximated by zero.

For quasi-static applications including actuators and hydrophones well below resonance and extensional resonators, the boundary condition stresses can often be approximated by zero in directions other than the second index. These applications may be solved most readily in terms of the piezoelectric constants d and g.

For thickness mode resonators, the strain in directions other than the second subscript may be approximated by zero. These applications may be solved in terms of the piezoelectric constants e and h, or the thickness coupling constant kt.

Longitudinal Actuator (well below resonance)

A laterally, unconstrained d33-mode actuator element at frequencies well below resonance will have a free displacement (force = 0) given by:

$$\Delta l = d_{33} \cdot V$$

If an actuator is composed of a stack of elements wired in parallel as shown in Figure 27, then Δ l will be increased proportionately.

If the displacement is blocked, the blocked force, Fb, (displacement = 0) will be:

$$F_b = d_{33} \cdot A \cdot V / (s^E_{33} \cdot t)$$

for a single element. For a stack, t is the thickness of a single element and compliance must include the joints.

Hydrophones and Sensors (well below resonance)

At frequencies well below resonance, a pressure sensor composed of a piezoceramic block exposed to hydrostatic or uniform acoustical pressure on all surfaces will generate an open circuit voltage given by:

$$V = -g_h \cdot t \cdot T_h$$

where g_h is given by $g_h = g_{33} + 2\, g_{31}$, and $-T_h$ is the hydrostatic pressure. As g_{33} and g_{31} have opposite signs, greater sensitivity can be achieved by shielding the lateral faces from pressure. A laterally unconstrained, g_{33}-mode sensor element will generate an open circuit voltage given by:

$$V = -g_{33} \cdot t \cdot T_3$$

Hydrophones with even greater sensitivity can be made by using geometries that create higher stress in the ceramic for a given applied pressure. An example is the “tonpilz” in which a ceramic pillar or stack is combined with a head of greater area. Other examples include the use of hollow piezoceramic spheres and cylinders.

Overall sensor performance depends on the ability to drive attached circuitry and signal-to-noise ratio. Consequently, the sensor capacitance and dissipation must also be considered to achieve a well designed system.

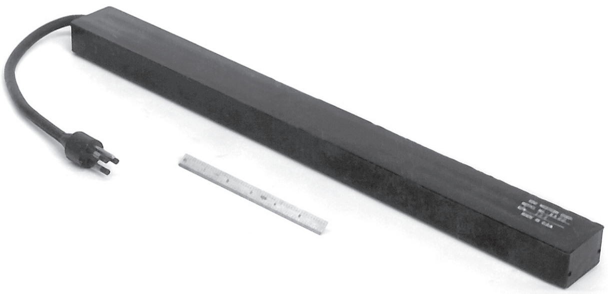
General Transducers and Resonators

Transducer design and manufacturing typically involves consideration of many environmental and acoustical performance factors. Multiple non-piezoelectric components are usually needed to achieve the desired performance. Engineering experience and lengthy computer models are used to simulate the interactions of all acoustical components and optimize the tuning interface to electronics. Transducer design references are provided in the Design References section on page 40.

SAMPLE TRANSDUCERS

L3Harris possesses all the necessary facilities and capability to support prototyping, qualification and production of a wide range of transducers for both commercial and military applications. Samples are shown below.

Contact L3Harris Acoustic Sensors for further information.

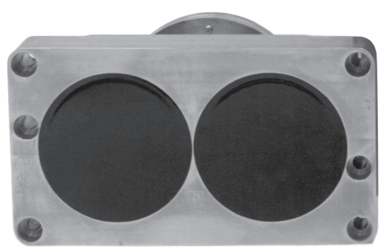


The Model 6400 Fan Beam Transducer is ideal for applications such as Side-Scan and Obstacle Avoidance Sonars. The active elements in this array are arranged to provide shading in both the horizontal and vertical planes.

The Model 6829 series of reciprocal transducers offer the system designer a choice of devices providing an omnidirectional beam pattern over a broad range of operating frequencies. These highly efficient transducers utilize spherical lead-zirconate-titanate ceramic elements which allow a high power output over broad frequency ranges or receiver capabilities.

This high performance COTS (commercial-off-the-shelf) Hydrophone is compact and economical. It is well suited for military towed arrays, stationary underwater platforms and geophysical applications.

The Model 6355 (TR-355) Transducer incorporates the latest advances in piezoelectric ceramic and ruggedizing techniques allowing these units to be used at high ambient pressures in hostile environments involved with bottom sounding.



L3Harris patented phased transducer array design is standard on all L3Harris Doppler sonar velocity logs. It automatically adjusts for variations in the speed of sound in water.

The transducer's dual-beam array minimizes measurement errors due to the vessel's pitch and roll. The transducer unit consists of two circular arrays of ceramics, arranged so that each circular array develops an opposing pair of beams.

PIEZOELECTRIC ACTUATORS

Key Features of the Piezoelectric Actuator:

> Displacement is proportional to applied voltage
> Fast rise time
> Large force – displacement
> High energy density output
> Excellent durability and stability
> Light weight and compact
> Broad operating range, -55°C to 75°C

Piezoelectric stack assemblies, or actuators, are a linear extension of the basic piezoelectric element. A number of piezoelectric elements are stacked mechanically in series and wired electrically in parallel using adhesive to bond the elements or co-fired monolithic multilayers to form an assembly. The actuator assembly can produce microns of displacement by applying a low voltage to the piezoelectric stack.

Piezoelectric actuators have consistent displacement, large force capability and extremely short response time. These devices develop a force that is in phase with acceleration requirements and therefore overcomes the static friction generally encountered in the initial stage of operation.

Typical Applications:

> X-Y transfer tables
> Precision positioning devices
> Polarization control equipment
> Piezoelectric valves
> Deformable mirrors
> Pressure sensors
> Linear stepping motors
> Acceleration sensors
> Relay contact drivers
> Displacement gauges

The key element of a piezo actuator is the piezoelectric element and its ability to change dimensions with voltage. For a given system of constraints on the applied voltage and operating environment versus deflection, the piezoelectric required coefficients are determined and from those, preliminary material selections are made.

A typical actuator as illustrated in Figure 27 is composed of "n" piezoelectric elements each of area "A" and thickness "t." The elements are mechanically connected in series and electrically connected in parallel. An applied voltage will cause the actuator to expand or contract,

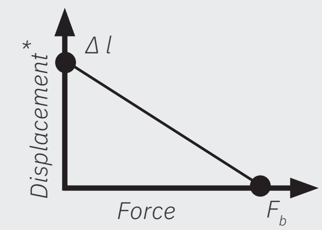
The actuator displacement "Δ l" for an applied voltage "V" is:

$$\Delta l = nd_{33} \cdot V$$

An EC-98 Actuator stack composed of 30 elements, .250 in diameter, .020 in thick with an applied voltage of 1000 volts would cause a displacement of 21.9 μ or 862 μin.

Actuator displacement will change by mass loading or increased clamping pressure. The blocked force generated by the actuator is:

$$F_b \approx \frac{\Delta l \cdot A}{nts^E_{33}}$$



* *Actual performance will depend on joints*

The electromechanical value of d33 and elastic constant sE33 are indicated in Table 3.

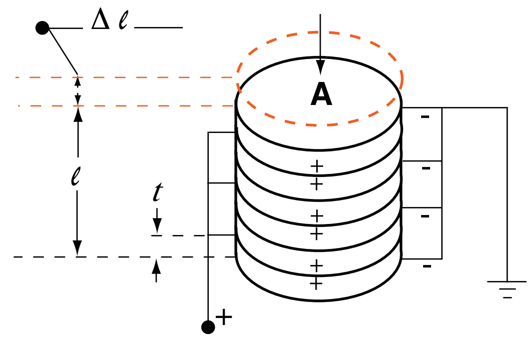


Figure 27: *Typical Actuator*

Electrical Termination

Interconnections between individual elements are attached to a common buss, one for positive, one for negative. Termination is provided through insulated wires, red for positive and black for negative, consistent with stack size and applied voltages.

Mechanical End Protection

Assemblies are supplied with unpoled ceramic end plates. End plates provide a wear surface, a base or anchor for mounting purposes and aid in dielectric protection.

Protective Coating

Each Actuator assembly is provided with a high dielectric dipped protective coating for both dielectric and environmental protection.

PIEZOELECTRIC BENDING ELEMENTS

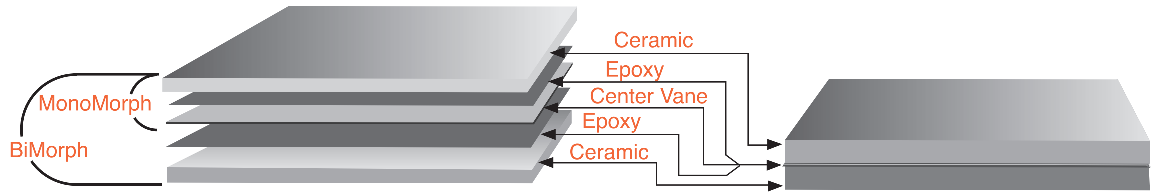


Figure 28: *Structure of MonoMorph and BiMorph Bending Elements*

Piezoelectric bending elements are electromechanical transducers that possess high motion and voltage sensitivity. The element's sandwich-like structure, in which one (mono) or two (bi) thin piezoelectric ceramic sheets are bonded to a center support vane, provides mechanical integrity and built-in leverage to amplify the motion and electrical output of the ceramic layers. The element structure is shown in Figure 28.

In motor applications one ceramic layer expands laterally and the other layer contracts when an electric field is applied to the element. The opposing strains result in a bending or deflection of the element that is proportional to the applied voltage. As actuators, the elements can generate large displacements and moderate forces at low levels of electrical drive. Typical applications include valves, relays, and micro-positioners.

In generator applications, a bending or deflection of the element places one of the ceramic layers in tension and the other layer in compression. As a result of the induced stresses, the element generates an output voltage that is proportional to the applied force. As sensors, the elements can generate electrical signals from sources of low mechanical impedance. Typical applications include impact and motion sensors, vibration meters, medical products and industrial sensing devices.

The most common bending element shapes are rectangular, square and circular (Figure 29). The elements are typically mounted in cantilever or simply supported configurations. Elements mounted in the cantilever beam configuration will generate four times the deflection and one-fourth the force obtained in the simple beam configuration.

The ceramic layers of a bending element can be electrically connected either in series or in parallel. The series element has one-fourth the capacitance and four times the impedance of the parallel element. In motor applications, the parallel element can generate the same deflections and forces as the series element with half the drive voltage. In sensor applications, the series element has twice the voltage sensitivity of the parallel element. Unless drive voltage limitations dictate the use of a parallel element, the series element is recommended due to its greater ease of manufacture in not having to access and connect to the center vane.

Ceramic Materials

The most popular materials are EC-65 (Navy Type II) and EC-76 (Navy Type VI). EC-65 is preferred for its greater ease of manufacture, higher service temperature and more stable temperature performance characteristics. In certain applications, our industry leading material, EC-98 electrostrictive composition, may be used to provide the greatest deflection per applied field.

Custom Assembly Capability

L3Harris can provide bending elements to meet your specific application needs. Contact L3Harris with details of your custom assembly for a prompt quotation. Custom applications may include:

> Center vanes using brass, stainless steel, kovar, invar, titanium

> Lead attachment

> Adhesives for high temperatures

Contact L3Harris for further information and datasheet.

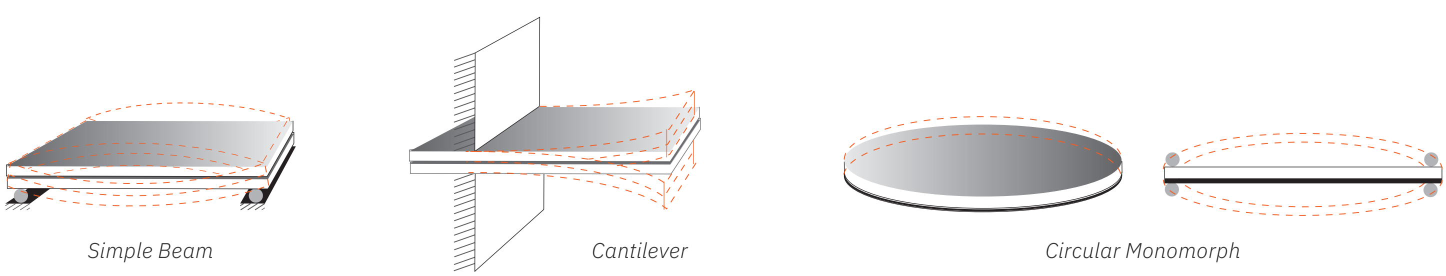


Figure 29: *Various configurations of bending elements*

ORDERING INFORMATION

L3Harris provides the highest quality components in the industry and manufactures a wide range of material, configuration, sizes and tolerances. In order for us to meet or exceed your expectations, we request as much information on your application and the required ceramic component desired as possible. The following items describe the key specifications we need to know to achieve this. If you are unsure of your requirements, L3Harris pleased to work with you to define your required material and configuration. If your specification is not as detailed as indicated, standard commercial practices will apply.

Describe Application

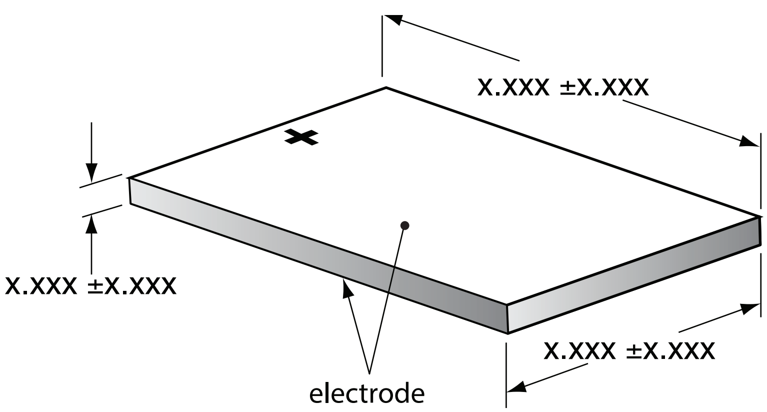
Briefly describe your application and its requirements. If known, please provide the transducer configuration and operational conditions. Any drawing or sketch will help.

Select Material

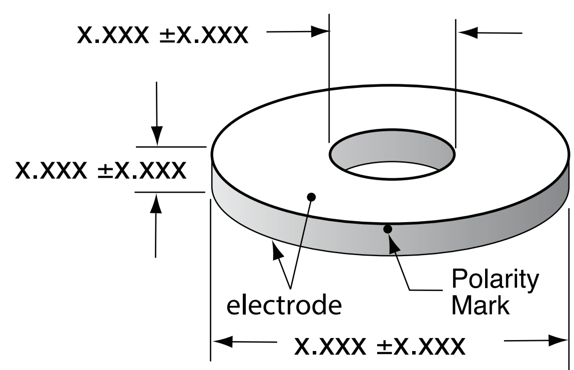
Please select your required piezoelectric material from L3Harris offering provided in the Material Types section (Table 3). Our sales and engineering staff will be able to assist you if needed.

Select Configuration

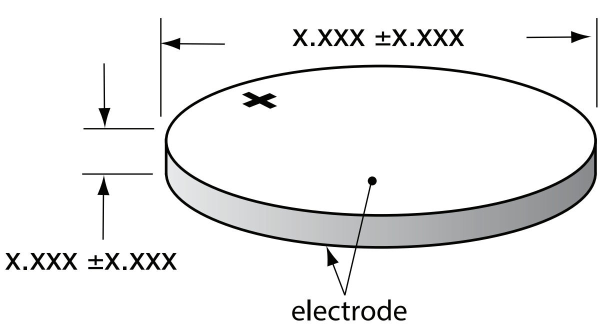
Select the desired configuration, dimensions and tolerances. Table 5 presents some typical as fired and machined tolerances. Provide any special dimensional tolerance, flatness, parallelism, perpendicularity and concentricity if required. L3Harris will apply standard machining tolerances if none are supplied.



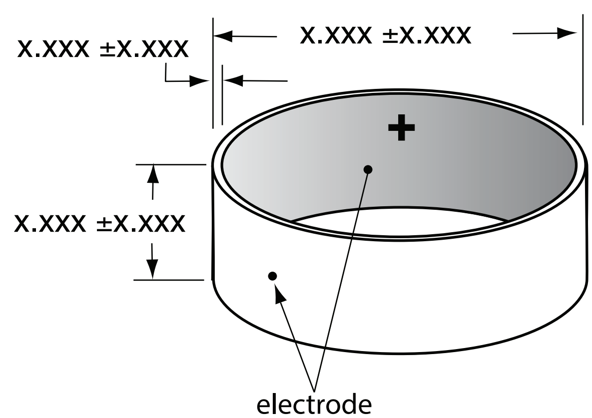
BAR



RING

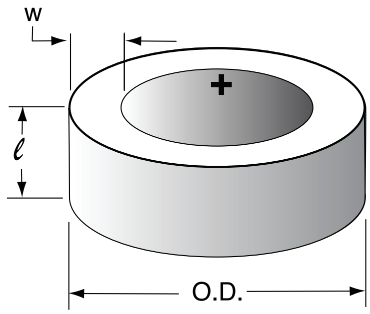


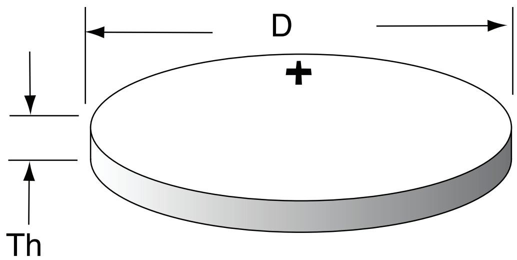
DISC

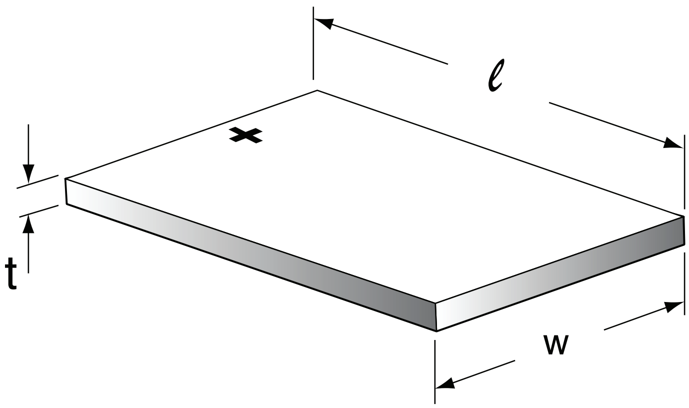


CYLINDER

Note: Surface finish of <125 micro-inches is standard







TUBE (O.D.)	CLASS III AS FIRED	CLASS LL MINIMAL MACHINING	CLASS I FULLY MACHINED
.250” – .500”	± .020”	± .010”	± .002”
.500” – 1.000”	± .030”	± .015”	± .003”
1.000” – 2.000”	± .050”	± .025”	± .003”
2.000” – 3.000”	± .070”	± .035”	± .004”
3.000” – 4.000”	± .090”	± .050”	± .004”
4.000” – 6.000”	± .125”	± .060”	± .005”
TUBE (WALL)			
.020” – .031”	± .005”	±.005”	± .002”
.031” – .063”	± .010”	± .005”	± .002”
.063” – .100”	± .015”	± .010”	± .003”
.100” – .125”	± .020”	± .015”	± .003”
.125” – .250”	± .030”	± .020”	± .004”
.250” – .350”	± .040”	± .030”	± .004”
.350” – .500”	± .050”	± .035”	± .005”
TUBE (LENGTH)			
.125” – .500”	± .010”	± .005”	± .002”
.250” – 2.000”	± .015”	± .010”	± .005”
2.000” – 4.000”	± .020”	± .015”	± .010”
4.000” – 6.000”	± .030”	± .015”	± .010”

DISC (DIA) PLATES (L OR W)	CLASS III AS FIRED	CLASS LL MINIMAL MACHINING	CLASS I FULLY MACHINED
.125” – 1.500”	± .015”	± .010”	± .003
1.500” – 2.500”	± .020”	± .015”	± .005”
2.500” – 3.500”	± .030”	± .020”	± .005”
3.500” – 4.500”	± .040”	± .025”	± .010”
4.500” – 6.000”	± .040”	± .030”	± .010”
DISC (THICKNESS)			
.010” – .015”	NA	± .002”	± .001”
.015” – .035”	NA	± .002”	± .001”
.035” – .080”	± .004”	± .003”	± .002”
.080” – .200”	± .010”	± .008”	± .003”
.200” – .500”	± .015”	± .010”	± .004”
.500” – 1.00”	± .025”	± .020”	± .005”

Sphere/hemisphere – sphere and hemisphere tolerances to be negotiated with L3Harris.

Flatness – the flatness tolerance will be within the thickness tolerance providing the diameter/thickness ratio is less than 10:1

Note: These tolerances are typical, manufacturing variationsto be expected.

Table 5: Standard Mechanical Tolerances

ELECTRODE

Provide information on the location and type of electrode required. L3Harris typically provides fired-on silver electrode which provides excellent adhesion. Conductivity is normally optimimal with a silver thickness of about .0003" – .0010".

In time, the silver electrode surface will tarnish if not protected from the environment. This tarnish can be removed by burnishing the area with a low abrasive material such as a soft eraser.

Electrical Specifications

Provide any electrical requirements and tolerances such as capacitance, dissipation factor, and the effective electromechanical coupling coefficient *(k_{eff})*.

> Typical tolerance for frequency is +/- 5% (tighter tolerances are available on request)

> Standard tolerance for capacitance is +/- 10% (tighter tolerances are available on request)

> Electromechanical coupling is normally listed as a minimum value

Marking

Components will normally be marked with the positive polarity on the electrode surface unless otherwise specified. Additional markings such as serial number, part number, pole date, lot identification, and manufacturer identification are available upon request.

Packaging

Ceramic components are packaged for shipment in containers that provide adequate protection against damage. Any special packaging requirements should be defined.

ANSWERS TO FREQUENTLY ASKED QUESTIONS

Soldering Instructions

The electrode quality is defined by adhesion which is typically monitored per DOD-1376 B (sh) and uses the following supplies:

> Soldering Iron – 600ºF is recommended

> Solder – 62/36/2 Pb/Sn/Ag solder is recommended

> Flux – a non-corrosive RMA rosin flux is recommended

> Abrasive device – fine sand paper, soft eraser, or glass brush to remove any tarnish

Burnish: Following manufacture the silver electroded surfaces form a white finish. Prior to lead attachment a small region of the "white" electrode should be lightly abraded using an eraser tip or other abrasive device to expose the high gloss silver. The silver is typically .0003" - .001" thick so care should be taken when abrading.

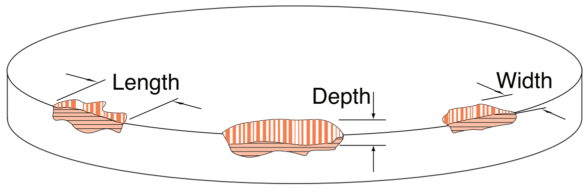
Clean: Clean the prepared surfaces with a solvent such as isopropyl alcohol.

Flux: Flux the small area to be soldered, Do not apply excessive heat to the solder field. Typically the solder tip is in contact with the ceramic electrode about .25 to .50 seconds.

Wire: Always use the finest, most flexible conductive wire leads. Ceramic crystals use 26 – 30 AWG leads typically, once cut to length, tinned and soldered to the ceramic surface, these leads require strain relief to prevent mechanical damage to the solder joint.

Ceramic Chip Defects

L3Harris will typically break all sharp edges or chamfer edges to minimize the occurrence of edge chips unless otherwise specified. Every effort is made to reduce the occurrence of edge chips when handling or machining the ceramic. Figure 31 shows typical acceptable chip dimensions.



Chip Length = the smaller of .150in. or 5% of the given part length/circumference

Chip Width = the smaller of .150in. or 10% of the given part length/diameter

Chip Depth = the smaller of .150in. or 30% of the given part depth

Tighter specifications are negotiable.

Figure 31: *Chip description*

Ceramic Testing

All ceramic parts are 100% electrically tested. Sample data is provided in hard copy on 30 pieces and typically includes low field measurements of capacitance, tan delta, fm, fn, keff, delta f/fn, Zfm, and Zfn, measured at the test date with the capacitance, fm, keff and delta f/fr aged to 10 days. Reasonable engineering tolerances are provided to each of these features if not specified and a frequency response is measured at only one of the multiple resonant modes. Procedures other than this can be negotiated, and additional data requirements (electronic format, sample quantity, etc) are available upon request.

Furthermore, L3Harris measures the frequencies of minimum and maximum impedance, fm and fn respectively, due to the difficulty in measuring the series (fs) and parallel resonances (fp) directly. The frequency differences are in the order: (fn-fm)>(fp-fs)>(fa-fr) and the three frequencies can be assumed to be nearly equal (< 1% difference) for ceramic of high coupling, mechanical and dielectric quality factors.

CAPABILITIES

Configuration Capabilities

L3Harris has processing capabilities that support a wide range of sizes and shapes. L3Harris can process piezoelectric materials into discs, rings, cylinders, bars, plates, and hemispheres. We can also produce both bimorph and stacked or multilayer actuator configurations. Discs range in diameter from 0.125 to 10 inches. Rectangular shapes can be produced up to 6 inch x 3.5 inch. These represent some of the over 6000 part numbers supported by L3Harris vast tooling inventory. Highlights of L3Harris current ceramic manufacturing capabilities include:

- Powder manufacturing capacity up to 1,000,000 lbs annually
- 9 hydraulic, mechanical, and isostatic presses
- 38 total kilns, including 18 multiple zoned controlled high temperature kilns
- High speed CNC machining centers supporting cylindrical grinding, slicing, lapping, dicing and surface grinding
- Multiple electrode application methods including spraying, screening and dipping. We can provide custom patterns on electrodes using abrasive trim technology
- 12 polarization stations

After the powder has been produced, piezoelectric component manufacturing requires 5 - 12 weeks to manufacture the part depending on factory loading, requirements for special powder, tooling, stock availability, or electrical performance requirements. The flow chart for L3Harris piezoelectric shapes production follows.

Following approval of a 1 kg sample of each raw material, a production quantity of those raw materials are received and an evaluation against known control materials is performed. Materials are weighed and verified, mixed and calcined (high temperature solid solution reaction). Particle size is verified following milling. Material is spray dried followed by sampling for electrical and mechanical features against a known standard. After this is performed the powder lot is approved and stored.

When an order is received the production process follows as this flow chart describes:

Press Powder into Shape

Green density control chart. Traveler paperwork initiated for tracking product flow. Size verification.

Bisque or Binder Burn Out Firing

Multiple zone control kiln monitoring interfaced with temperature database interface, alarms and UPS backup.

High Temperature Firing (Sintering)

Multiple zone control kiln monitoring interfaced with temperature database, automated atmosphere flow and alarms. Validation of all thermocouples on scheduled cycle, fired density measurement, size histograms.

Machining or Grinding to Size

CNC control grinding center. Histograms or control chart generated for all machined dimensions and geometric tolerances.

Next Page

Electrode

Control chart of silver thickness using X-ray fluorescence

Silver/Electrode Firing

Multiple zone kiln monitoring interfaced with temperature database and alarms.

Polarization

Define optimum poling conditions

Mechanical Inspection

Optical comparator and coordinate measurement machine

Electrical Test

Electrical measurement system, designed by L3Harris, interfaced to network for data collection and statistical analysis. Control chart and Process Capability on capacitance, resonant frequency and piezoelectric coupling factor

All work in process is tracked by an internal database (ERP system) that can provide real time information on location of product, yield, schedule and work instructions.

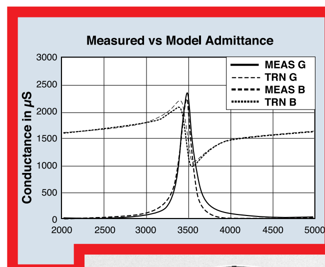
Identified key quality control measures are tracked by statistical control, process capability studies and other statistical methods, and are used to maintain process control through out the manufacturing process. Process control teams use multivariable testing in keeping with L3Harris commitment to quality.

VERTICAL INTEGRATION

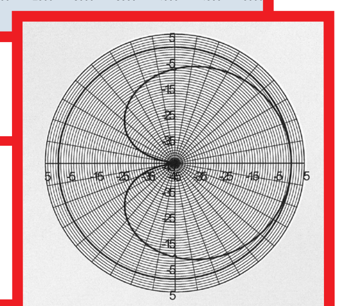
L3Harris value added manufacturing capability leverages our ceramic material experience to provide vertically integrated transducer sub-assemblies.

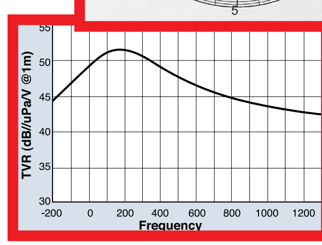
Ceramic shapes are manufactured to tight specifications

Transducers are designed in-house to meet customer performance specifications



Performance Modeling is used to predict transducer capabilities well before prototyping or production



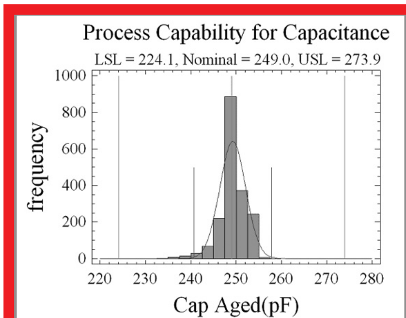


Detailed component design and documentation reduces part count and fabrication cost to meet performance needs at competitive prices

Next Page

Product sub-assembly integrates ceramic elements with mechanical hardware to facilitate lead attachment and pre-stressing

Top assembly provides final packaging for end user installation and operation

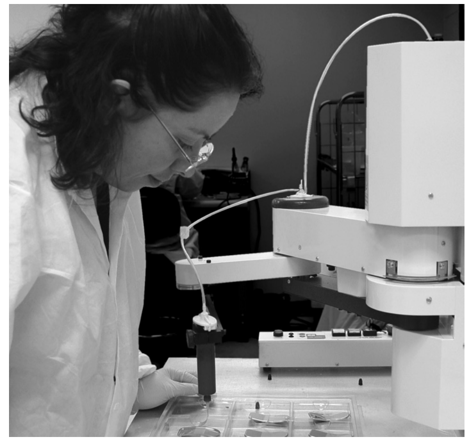


Statistical process control methods ensure product consistency and performance compliance

Final environmental stress screening eliminates field failures prior to final delivery

MANUFACTURING

Our facilities cover all aspects of transducer and sonar array design, development, fabrication and test. In addition, the production of a wide variety of value added assemblies for commercial and medical applications are produced by our experienced teams of manufacturing personnel. Our fully equipped machine shop, along with our encapsulation and housing capabilities, allows us to design custom systems to customer specifications. From simple wire lead attachments, to intricately wired sub-assemblies, to fully developed on-board ship's sonar systems, we have the in-house capability to handle and control each step of the manufacturing process.



L3Harris experienced manufacturing staff is crosstrained for many production skill positions

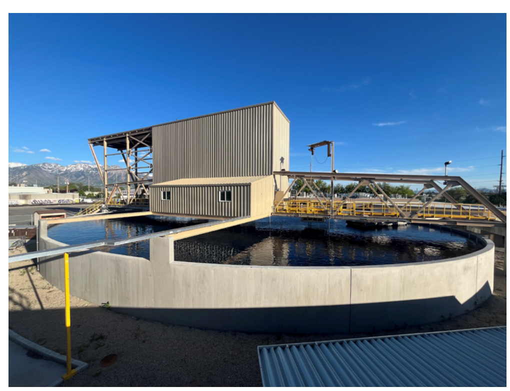
ENGINEERING/DESIGN

L3Harris maintains a highly trained engineering staff responsible for research and development, design, and production engineering. Our engineers work closely with customers to define and develop the best solution based on customer requirements.

TESTING

L3Harris has extensive test facilities capable of conducting virtually any test required in the performance validation of any hydrophone, transducer or sub-system. These facilities include computer controlled test stations used for 100% testing of all ceramic pieces produced by L3Harris.

L3Harris operates two in-water acoustic test and calibration facilities. These facilities are fully equipped to complete sonar transducer development and production testing. Both facilities are outfitted with computer controlled calibration systems.



L3Harris largest in-water acoustic test facility is 60 feet long and 35 feet deep.

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APPENDIX I: THE PIEZOELECTRIC CONSTITUTIVE EQUATIONS AND THEIR CONSTANTS

Piezoelectric Constitutive Equations:

The quasi-electrostatic approximation is assumed, and magnetic and thermal effects are ignored. The summation convention applies to repeated subscripts. Four alternate forms of constitutive equation pairs are:

$$\Delta S_i = s^E_{ij}\,\Delta T_j + d_{mi}\,\Delta E_m$$

$$\Delta D_m = d_{mi}\,\Delta T_i + \varepsilon^T_{mk}\,\Delta E_k$$

$$\Delta S_i = s^D_{ij}\,\Delta T_j + g_{mi}\,\Delta D_m$$

$$\Delta E_m = -\,g_{mi}\,\Delta T_i + \beta^T_{mk}\,\Delta D_k$$

$$\Delta T_i = c^E_{ij}\,\Delta S_j - e_{mi}\,\Delta E_m$$

$$\Delta D_m = e_{mi}\,\Delta S_i + \varepsilon^S_{mk}\,\Delta E_k$$

$$\Delta T_i = c^D_{ij}\,\Delta S_j - h_{mi}\,\Delta D_m$$

$$\Delta E_m = -\,h_{mi}\,\Delta S_i + \beta^S_{mk}\,\Delta D_k$$

Definitions of piezoelectric constants:

$$d_{mi} = (\partial S_i/\partial E_m)_T = (\partial D_m/\partial T_i)_E$$

$$g_{mi} = (-\partial E_m/\partial T_i)_D = (\partial S_i/\partial D_m)_T$$

$$e_{mi} = (-\partial T_i/\partial E_m)_S = (\partial D_m/\partial S_i)_E$$

$$h_{mi} = (-\partial T_i/\partial D_m)_S = (-\partial E_m/\partial S_i)_D$$

Interrelationships among piezoelectric constants:

$$d_{mi} = \varepsilon^T_{nm}\,g_{ni} = e_{mj}\,s^E_{ji}$$

$$g_{mi} = \beta^T_{nm}\,d_{ni} = h_{mj}\,s^D_{ji}$$

$$e_{mi} = \varepsilon^S_{nm}\,h_{ni} = d_{mj}\,c^E_{ji}$$

$$h_{mi} = \beta^S_{nm}\,e_{ni} = g_{mj}\,c^D_{ji}$$

APPENDIX II: USEFUL RELATIONSHIPS FOR POLED FERROELECTRIC CERAMIC

Symmetry Relations for poled ferroelectric ceramic [(∞m) symmetry]:

$$s = \begin{Bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{11} & s_{13} & 0 & 0 & 0 \\ s_{13} & s_{13} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}-s_{12}) \end{Bmatrix}$$

$$d = \begin{Bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{Bmatrix}$$

$$\varepsilon = \begin{Bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{Bmatrix}$$

The independent elastic, piezoelectric, and dielectric constants are: s_{11}, s_{33}, s_{55}, s_{12}, s_{13}; d_{31}, d_{33}, d_{15}; ε_{11}, *and* ε_{33}. *The remaining coefficients are given by* $s_{22} = s_{11}$; $s_{23} = s_{13}$; $s_{44} = s_{55}$; $s_{66} = 2(s_{11} - s_{12})$; $d_{32} = d_{31}$, $d_{24} = d_{15}$; $\varepsilon_{22} = \varepsilon_{11}$.

MATERIAL COUPLING FACTORS:

The material coupling factor may be defined as:

$$k = U_m / \sqrt{(U_d U_e)}$$

Where:

U_m = *mutual energy,*

U_d = *dielectric energy, and*

U_e = *elastic energy.*

MATERIAL COUPLING FACTOR	ELASTIC BOUNDARY CONDITION
$k_{31}^2 = d_{31}^2/(\varepsilon^T_{33}\, s^E_{11})$	T_1 is the only nonzero stress
$k_{33}^2 = d_{33}^2/(\varepsilon^T_{33}\, s^E_{33})$	T_3 is the only nonzero stress
$k_p^2 = 2d_{31}^2/[\varepsilon^T_{33}\,(s^E_{11} + s^E_{12})] = k_{31}^2[\,2/(1 - \sigma^p)]$	$T_1 = T_2$ are the only nonzero stresses
$k_t^2 = h_{33}^2/(\beta^S_{33}\, c^D_{33})$	S_3 is the only nonzero strain
$k_{15}^2 = h_{15}^2/(\beta^S_{11}\, c^D_{55}) = d_{15}^2/(\varepsilon^T_{11}\, s^E_{44})$	S_5 is the only nonzero strain

MATERIAL COUPLING FACTOR	SHAPE
$k_{31}^2 = \frac{A}{1+A}$ or $k_{31}^2 / (1-k_{31}^2) = A$ where $A = (\pi / 2)\,(f_p / f_s) \tan[(\pi / 2)\,(f_p - f_s) / f_s]$	Side electroded bar
$k_{31}^2 = (f_p^2 - f_s^2) / f_p^2$	Radially poled, thin-wall ring
$k_p^2 = (f_p^2 - f_s^2) / f_p^2$	Thin-wall sphere
$k_{33}^2 = (\pi / 2)\,(f_s / f_p) \tan[(\pi / 2)\,(f_p - f_s) / f_p]$	End electroded rod
$k_t^2 = (\pi / 2)\,(f_s / f_p) \tan[(\pi / 2)\,(f_p - f_s) / f_p]$	Disc or plate

MATERIAL COUPLING FACTOR	WAVE SPEED	SHAPE
Rod, 33-extensional	$v^D = 1 / (\rho s^D_{33})^{1/2}$	$f_p = n\, v^D/2l$, n = odd integer
Disc, 33-thickness	$v^D = (c^D_{33} / \rho)^{1/2}$	$f_p = n\, v^D/2t$, n = odd integer
Plate, 15-thickness shear	$v^D = (c^D_{55} / \rho)^{1/2}$	$f_p = n\, v^D/2t$, n = odd integer
Bar, 31-extensional	$v^E = 1 / (\rho s^E_{11})^{1/2}$	$f_s = 1/[2\pi a\,(\rho s^E_{11})^{1/2}]$
Ring, 31-hoop	–	$f_s = 1/[2\pi a\,(\rho s^E_{11})^{1/2}]$
Hollow sphere, breathing	–	$f_s = 1/[2\pi a\,(\rho\,(s^E_{11} + s^E_{12}))^{1/2}]$

Open- and short-circuit elastic constant relationships:

$$s^D_{11} = s^E_{11} (1- k_{31}^2)$$

$$s^D_{12} = s^E_{12} - k_{31}^2 s^E_{11}$$

$$s^D_{13} = s^E_{13} - d_{31} d_{33} / \varepsilon^T_{33}$$

$$s^D_{33} = s^E_{33} (1- k_{33}^2)$$

$$c^E_{33} = c^D_{33} (1- k_t^2)$$

$$s^D_{55} = s^E_{55} (1- k_{15}^2)$$

Clamped and free permittivity relationships:

$$\varepsilon^S_{11} = (1- k_{15}^2) \varepsilon^T_{11}$$

$$\varepsilon_{33} = (1- k_{33}^2) \varepsilon^T_{33} \text{ (Rod, longitudinally clamped)}$$

$$\varepsilon^S_{33} = (1- k_p^2) (1- k_t^2) \varepsilon^T_{33} \text{ (fully clamped)}$$

Hydrostatic relationships:

$$d_h = 2d_{31} + d_{33}$$

$$g_h = 2g_{31} + g_{33}$$

PIEZOELECTRIC CERAMIC SHAPES VALUE-ADDED ASSEMBLIES MILITARY SONARS & COMMUNICATIONS

Notes

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