PIEZOELECTRIC TECHNOLOGY PRIMER

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Piezoelectricity

The piezoelectric effect is a property that exists in many materials. The name is made up of two parts; piezo, which is derived from the Greek work for pressure, and electric from electricity. The rough translation is, therefore, pressure - electric effect. In a piezoelectric material, the application of a force or stress results in the development of a charge in the material. This is known as the direct piezoelectric effect. Conversely, the application of a charge to the same material will result in a change in mechanical dimensions or strain. This is known as the indirect piezoelectric effect.

Several ceramic materials have been described as exhibiting a piezoelectric effect. These include lead-zirconate-titanate (PZT), lead-titanate ($PbTiO_2$), lead-zirconate ($PbZrO_3$), and barium-titanate ($BaTiO_3$). These ceramics are not actually piezoelectric but rather exhibit a polarized electrostrictive effect. A material must be formed as a single crystal to be truly piezoelectric. Ceramic is a multi crystalline structure made up of large numbers of randomly orientated crystal grains. The random orientation of the grains results in a net cancelation of the effect. The ceramic must be polarized to align a majority of the individual grain effects. The term piezoelectric has become interchangeable with polarized electrostrictive effect in most literature.

Piezoelectric Effect

It is best to start with an understanding of common dielectric materials in order to understand the piezoelectric effect. The defining equations for high permittivity dielectrics are:

$$C = \frac{K \varepsilon_r A}{t} = \frac{\varepsilon_O \varepsilon_r A}{t} = \frac{\varepsilon A}{t}$$

and

$$Q = C V \longrightarrow Q = \frac{\varepsilon A V}{t}$$

where:
- C = capacitance
- A = capacitor plate area
- ε_r = relative dielectric constant
- ε_O = dielectric constant of air = 8.85×10^{-12} farads / meter
- ε = dielectric constant
- V = voltage
- t = thickness or plate separation
- Q = charge

In addition, we can define electric displacement, D, as charge density or the ratio of charge to the area of the capacitor:

$$D = \frac{Q}{A} = \frac{\varepsilon V}{t}$$

and further define the electric field as:

$$E = \frac{V}{t} \qquad \text{or} \qquad D = \varepsilon E$$

These equations are true for all isotropic dielectrics. Piezoelectric ceramic materials are isotropic in the unpolarized state, but they become anisotropic in the poled state. In anisotropic materials, both the electric field and electric displacement must be represented as vectors with three dimensions in a fashion similar to the mechanical force vector. This is a direct result of the dependency of the ratio of dielectric displacement, D, to electric field, E, upon the orientation of the capacitor plate to the crystal (or poled ceramic) axes. This means that the general equation for electric displacement can be written as a state variable equation:

$$D_i = \varepsilon_{ij} E_j$$

The electric displacement is always parallel to the electric field, thus each electric displacement vector, D_i, is equal to the sum of the field vector, E_j, multiplied by its corresponding dielectric constant, ε_{ij}:

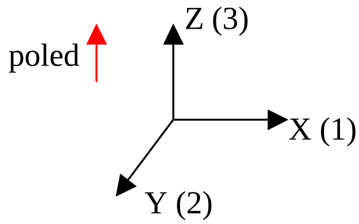
$$D_1 = \varepsilon_{11} E_1 + \varepsilon_{12} E_2 + \varepsilon_{13} E_3$$
$$D_2 = \varepsilon_{21} E_1 + \varepsilon_{22} E_2 + \varepsilon_{23} E_3$$
$$D_3 = \varepsilon_{31} E_1 + \varepsilon_{32} E_2 + \varepsilon_{33} E_3$$

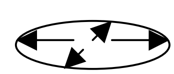
Fortunately, the majority of the dielectric constants for piezoelectric ceramics (as opposed to single crystal piezoelectric materials) are zero. The only non-zero terms are:

$$\varepsilon_{11} = \varepsilon_{22} \;,\; \varepsilon_{33}$$

Axis Nomenclature

The piezoelectric effect, as stated previously, relates mechanical effects to electrical effects. These effects, as shown above, are highly dependent upon their orientation to the poled axis. It is, therefore, essential to maintain a constant axis numbering scheme.



#	Axis
1	X
2	Y
3	Z (poled)
4	Shear Around X
5	Shear Around Y
6	Shear Around Z
P	Radial Vibration 

for electro-mechanical constants:

d_{ab}, a = electrical direction; b = mechanical direction

Electrical - Mechanical Analogies

Piezoelectric devices work as both electrical and mechanical elements. There are several electrical - mechanical analogies that are used in designing modeling the devices.

Electrical Unit		Mechanical Unit	
e	Voltage (Volts)	f	Force (Newtons)
i	Current (Amps)	v	Velocity (Meters / Second)
Q	Charge (Coulombs)	s	Displacement (Meters)
C	Capacitance (farads)	C_M	Compliance (Meters / Newton)
L	Inductance (henrys)	M	Mass (Kg)
Z	Impedance	Z_M	Mechanical Impedance

$$i = \frac{dQ}{dt} \qquad v = \frac{ds}{dt}$$

$$e = L\frac{di}{dt} = L\frac{d^2Q}{dt^2} \qquad f = M\frac{dv}{dt} = M\frac{d^2s}{dt^2}$$

Coupling

Coupling is a key constant used to evaluate the "quality" of an electro-mechanical material. This constant represents the efficiency of energy conversion from electrical to mechanical or mechanical to electrical.

$$k^2 = \frac{\text{Mechanical Energy Converted to Electrical Charge}}{\text{Mechanical Energy Input}}$$

or

$$k^2 = \frac{\text{Electrical Energy Converted to Mechanical Displacement}}{\text{Electrical Energy Input}}$$

Electrical, Mechanical Property Changes With Load

Piezoelectric materials exhibit the somewhat unique effect that the dielectric constant varies with mechanical load and the Young's modulus varies with electrical load.

Dielectric Constant

$$\varepsilon_{r\ FREE}\,(1 - k^2) = \varepsilon_{r\ CLAMPED}$$

This means that the dielectric "constant" of the material reduces with mechanical load. Here "Free" stands for a state when the material is able to change dimensions with applied field. "Clamped" refers to either a condition where the material is physically clamped or is driven at a frequency high enough above mechanical resonance that the device can't respond to the changing E field.

Elastic Modulus (Young's Modules)

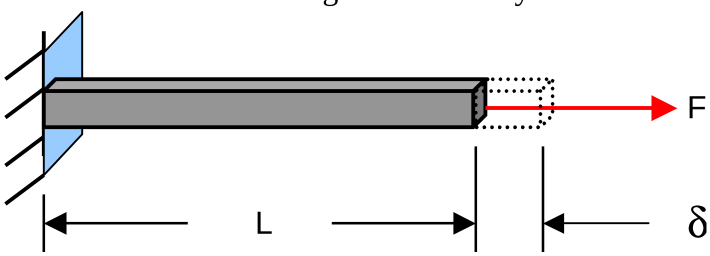
$$Y_{OPEN}\,(1-k^2) = Y_{SHORT}$$

This means that the mechanical "stiffness" of the material reduces when the output is electrically shorted. This is important in that both the mechanical Q_M and resonate frequency will change with load. This is also the property that is used in the variable dampening applications.

Elasticity

All materials, regardless of their relative hardness, follow the fundamental law of elasticity. The elastic properties of the piezoelectric material control how well it will work in a particular application. The first concepts, which need to be defined, are stress and strain.

for a given bar of any material:



F = Applied Force
A = Area To Which Force Is Applied
δ = Elongation

$$\text{Stress} = \sigma = F / A$$

$$\text{Strain} = \lambda = \delta / L$$

The relationship between stress and strain is Hooke's Law which states that, within the elastic limits of the material, strain is proportional to stress.

$$\lambda = S\,\sigma$$

or, for an anisotropic material

$$\lambda_i = S_{ij}\,\sigma_j$$

Note: The constant relating stress and strain is the modulus of elasticity or Young's modulus and is often represented by S, E or Y.

Piezoelectric Equation

It has been previously shown that when a voltage is applied across a capacitor made of normal dielectric material, a charge results on the plates or electrodes of the capacitor. Charge can also be produced on the electrodes of a capacitor made of a piezoelectric material by the application of stress. This is known as the Direct Piezoelectric Effect.

Conversely, the application of a field to the material will result in strain. This is known as the Inverse Piezoelectric Effect. The equation, which defines this relationship, is the piezoelectric equation.

$$D_i = d_{ij}\,\sigma_j$$

where:

$D_i \equiv$ Electric Displacement (or Charge Density)

$d_{ij} \equiv$ Piezoelectric Modulus, the ratio of strain to applied field or charge density to applied mechanical stress

Stated differently, d measures charge caused by a given force or deflection caused by a given voltage. We can, therefore, also use this to define the piezoelectric equation in terms of field and strain.

$$Di = \frac{\sigma_j\,\lambda_i}{E_j}$$

Earlier, electric displacement was defined as

$$Di = \varepsilon_{ij}\,E_j$$

therefore,

$$e_{ij}\,E_j = d_{ij}\,\sigma$$

and

$$Ej = \frac{d_{ij}}{\varepsilon_{ij}}\,\sigma_j$$

which results in a new constant

$$gij = \frac{d_{ij}}{\varepsilon_{ij}}$$

This constant is known as the piezoelectric constant and is equal to the open circuit field developed per unit of applied stress or as the strain developed per unit of applied charge density or electric displacement. The constant can then be written as:

$$g = \frac{\text{field}}{\text{stress}} = \frac{\text{volts / meter}}{\text{newtons / meter}^2} = \frac{\Delta L / L}{\varepsilon\, V / t}$$

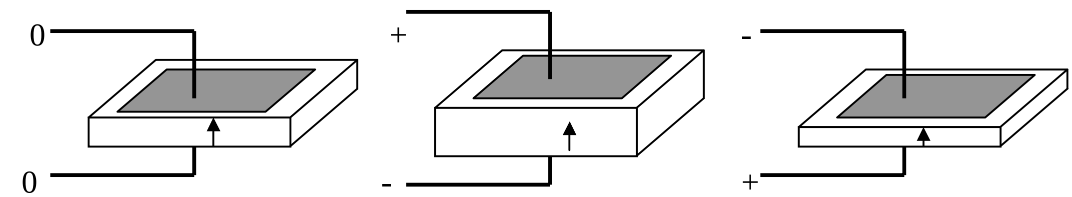
Fortunately, many of the constants in the formulas above are equal to zero for PZT piezoelectric ceramics. The non-zero constants are:

$$s_{11} = s_{22},\ s_{33},\ s_{12},\ s_{13} = s_{23},\ s_{44},\ s_{66} = 2\,(s_{11} - s_{12})$$

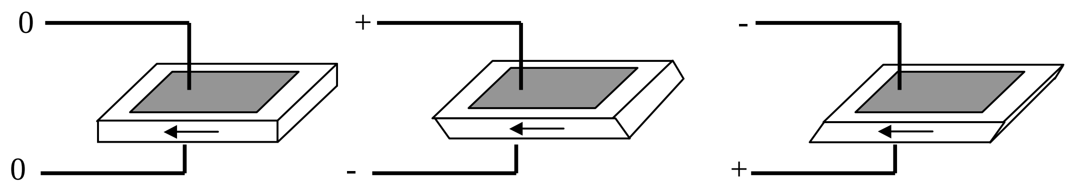
$$d_{31} = d_{32},\ d_{33},\ d_{15} = d_{24}$$

Basic Piezoelectric Modes

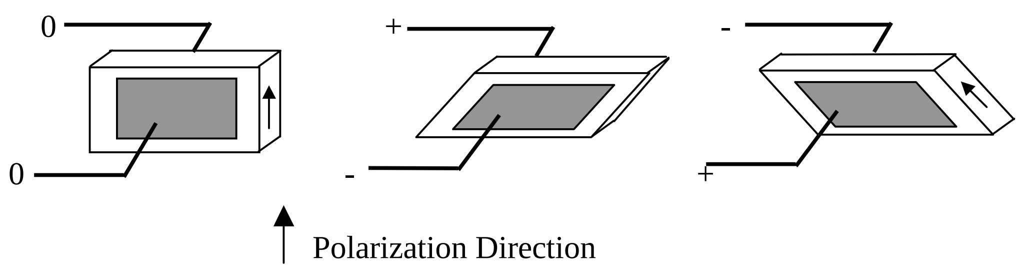
Thickness Expansion



Thickness Shear



Face Shear



Polarization Direction

Poling

Piezoelectric ceramic materials, as stated earier, are not piezoelectric until the random ferroelectric domains are aligned. This alignment is accomplished through a process known as "poling". Poling consists of inducing a D.C. voltage across the material. The ferroelectric domains align to the induced field resulting in a net piezoelectric effect. It should be noted that not all the domains become exactly aligned. Some of the domains only partially align and some do not align at all. The number of domains that align depends upon the poling voltage, temperature, and the time the voltage is held on the material. During poling the material permanetly increases in dimension between the poling electrodes and decreases in dimensions parallel to the electrodes. The material can be de-poled by reversing the poling voltage, increasing the temperature beyond the materials Currie point, or by inducing a large mechanical stress.

Post Poling

Applied Voltage:

Voltage applied to the electrodes at the same polarity as the original poling voltage results in a further increase in dimension between the electrodes and decreases the dimensions parallel to the electrodes. Applying a voltage to the electrodes in an opposite direction decreases the dimension between the electrodes and increases the dimensions parallel to the electrodes.

Applied Force:

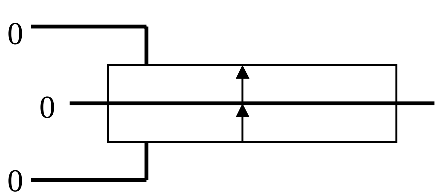
Applying a compressive force in the direction of poling (perpendicular to the poling electrodes) or a tensile force parallel to the poling direction results in a voltage generated on the electrodes which has the same polarity as the original poling voltage. A tensile force applied perpendicular to the electrodes or a compressive force applied parallel to the electrodes results in a voltage of opposite polarity.

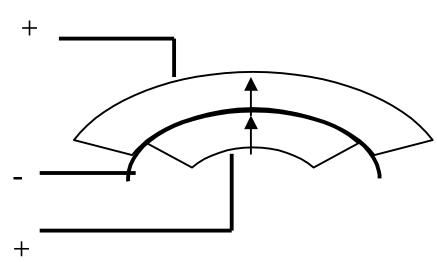
Shear:

Removing the poling electrodes and applying a field perpendicular to the poling direction on a new set of electrodes will result in mechanical shear. Physically shearing the ceramic will produce a voltage on the new electrodes.

Piezoelectric Benders

Piezoelectric benders are often used to create actuators with large displacement capabilities. The bender works in a mode which is very similar to the action of a bimetallic spring. Two separate bars or wafers of piezoelectric material are metallized and poled in the thickness expansion mode. They are then assembled in a + -+ - stack and mechanically bonded. In some cases, a thin membrane is placed between the two wafers. The outer electrodes are connected together and a field is applied between the inner and outer electrodes. The result is that for one wafer the field is in the same direction as the poling voltage while the other is opposite to the poling direction, This means that one wafer is increasing in thickness and decreasing in length while the other wafer is decreasing in thickness and increasing in length, resulting in a bending moment.





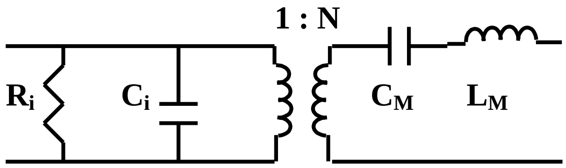
Loss

There are two sources for loss in a piezoelectric device. One is mechanical, the other is electrical.

Mechanical Loss: $Q_M = \frac{\text{Mechanical Stiffness Reactance or Mass Reactance}}{\text{Mechanical Resistance}}$

Electrical Loss: $\tan\delta = \frac{\text{Effective Series Resistance}}{\text{Effective Series Reactance}}$

Simplified Piezoelectric Element Equivalent Circuit



R_i = Electrical Resistance

C_i = Input Capacitance = $\frac{\varepsilon_O \varepsilon_r A}{t}$

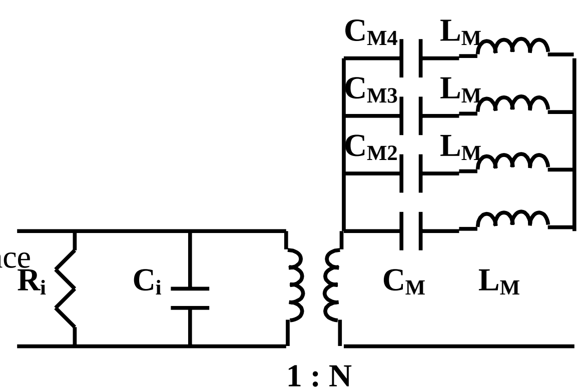
ε_O = 8.85 X 10-12 farads / meter
A = Electrode Area
t = Dielectric Thickness

L_M = Mass (Kg)

C_M = Mechanical Compliance = 1 / Spring Rate (M / N)

N = Electro-mechanical Linear Transducer Ratio (newtons/volt or coulomb/meter)

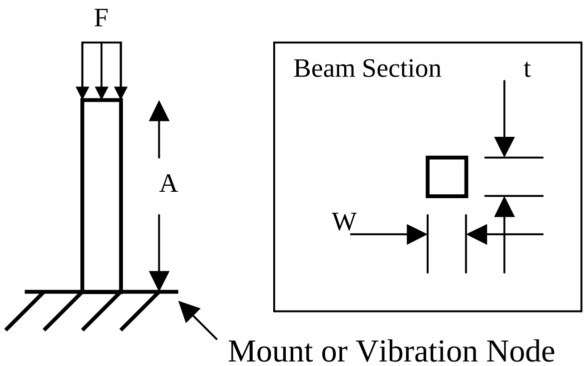
This model has been simplified and it is missing several factors. It is only valid up to and slightly beyond resonance. The first major problem with the model is related to the mechanical compliance (C_M). Compliance is a function of mounting, shape, deformation mode (thickness, free bend, cantilever, etc.) and modulus of elasticity. The modulus of elasticity is, however, anisotropic and it varies with electrical load. The second issue is that the resistance due to mechanical Q_M has been left out. Finally, there are many resonant modes in the transformers, each of which has its own C_M as shown below.



Mechanical Compliance

Mechanical compliance, which is the inverse of spring constant, is a function of the shape, mounting method, modulus and type of load.   Some simple examples are shown below.

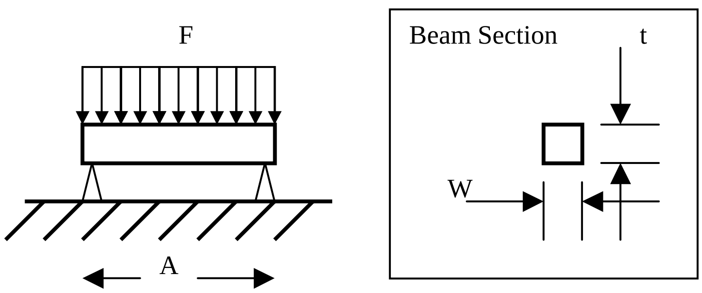
Simple Beam - Uniform End Load



$$C_M = \frac{A}{AY_{ij}} = \frac{A}{W\,t}$$

$$L_M = \rho\,A\,W\,t$$

Simple Beam - Uniform Load - End Mounts



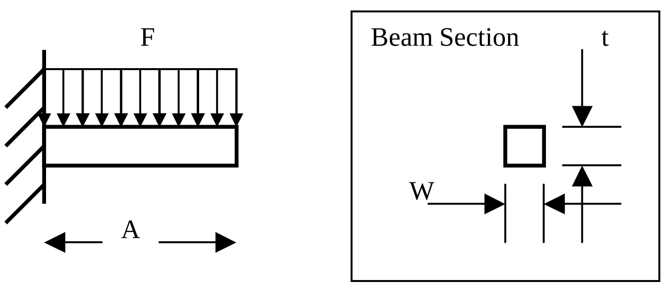
$$C_M = \frac{5\ \ A^3}{384\ Y_{ij}\ I}$$

I = Moment of Inertia

$$= \frac{W\ t3}{12}$$

$$C_M = \frac{5\ \ A^3}{32\ W\ t^3}$$

Simple Beam - Uniform Load - Cantilever Mount



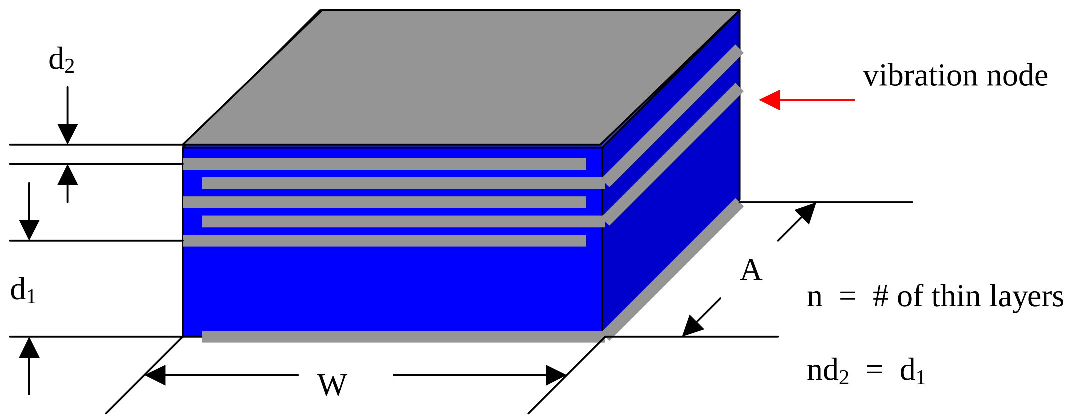
$$C_M = \frac{A^3}{8Y_{ij}I}$$

$$= \frac{3\ \ A^3}{2\ Y_{ij}\ W\ t^3}$$

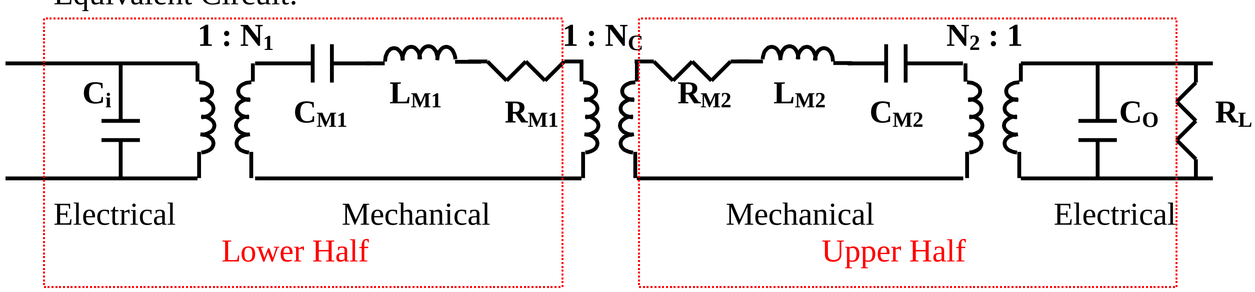
The various elements that have been explained can now be combined into the design of a complete piezoelectric device. The simple piezoelectric stack transformer will be used to demonstrate the way they are combined to create a functional model.

Simple Stack Piezoelectric Transformer

The piezoelectric transformer acts as an ideal tool to explain the modeling of piezoelectric devices in that it utilizes both the direct and indirect piezoelectric effects. The transformer operates by first converting electrical energy into mechanical energy in one half of the transformer. This energy is in the form of a vibration at the acoustic resonance of the device. The mechanical energy produced is then mechanically coupled into the second half of the transformer. The second half of the transformer then reconverts the mechanical energy into electrical energy. The figure below shows the basic layout of a stack transformer. The transformer is driven across the lower half (dimension d_1) resulting in a thickness mode vibration. This vibration is coupled into the upper half and the output voltage is taken across the thinner dimension d_2.



Equivalent Circuit:



The equivalent circuit model for the transformer (shown above) can be thought of as two piezoelectric elements that are assembled back to back. These devices are connected together by an ideal transformer representing the mechanical coupling between the upper and lower halves. The input resistance, R_i, and the output resistance, R_O, are generally very large and have been left out in this model. The resistor RL represents the applied load. Determining the values of the various components can be calculated as shown previously.

Input / Output Capacitance:

$$Ci = \varepsilon_O \varepsilon_r \frac{\text{Input Area}}{\text{Input Thickness}} = \varepsilon_O \varepsilon_r \frac{A\,W}{d_1}$$

similarly,

$$C_O = \varepsilon_O \varepsilon_r \frac{\text{Output Area}}{\text{Output Thickness}} = \varepsilon_O \varepsilon_r \frac{n\,A\,W}{d_2}$$

Mechanical Compliance:

The mechanical compliance, C_M, can be represented by a simple beam subjected to a uniform axial load. This is because the thickness expansion mode will apply uniform stress across the surface. It should be noted that the beam length is measured with respect to the vibration node. The vibration node is used as this is the surface which does not move at resonance and can, therefore, be thought of as a fixed mounting surface.

$$C_M = \frac{\text{Beam Length}}{\text{Beam Area}\ \ Y_{33}}$$

$$C_{M1} = \frac{d_1}{AW\,Y_{33}}$$

$$C_{M2} = \frac{d_2}{AW\,Y_{33}}$$

Note: Even if $nd_2 \neq d_1$ the vibration node will still be located in the mechanical center of the transformer.

Mass:

$$L_{M1} = \rho\,A\,W\,d_1$$

$$L_{M2} = \rho\,A\,W\,nd_2 = \rho\,A\,W\,d_1$$

Resistance:

The resistances in the model are a function of the mechanical Q_M and Q of the material at resonance and will be calculated later.

Ideal Transformer Ratio:

The transformer ratio, N_1, can be thought of as the ratio of electrical energy input to the resulting mechanical energy output. This term will then take the form of newtons per volt and can be derived form the piezoelectric constant, g.

as before:

$$g = \frac{\text{Electric Field}}{\text{Stress}} = \frac{\text{Volts / Meter}}{\text{Newtons / Meter}^2}$$

therefore:

$$\frac{1}{g} = \frac{n / m}{V / m}$$

$$N_1 = \frac{1}{g} \frac{\text{Area Of Applied Force}}{\text{Length Of Generated Field}}$$

or

$$N_1 = \frac{A\ W}{g_{33}\ d_1}$$

The output section converts mechanical energy back to electrical energy and the ratio would normal be calculated in an inverse fashion to N_1. In the model, however, the transformer ratio is shown as $N_2 : 1$. This results in a calculation for N_2 that is identical to the calculation of N_1.

$$N_2 = \frac{1}{g} \frac{\text{Area Of Applied Force}}{\text{Length Of Generated Field}}$$

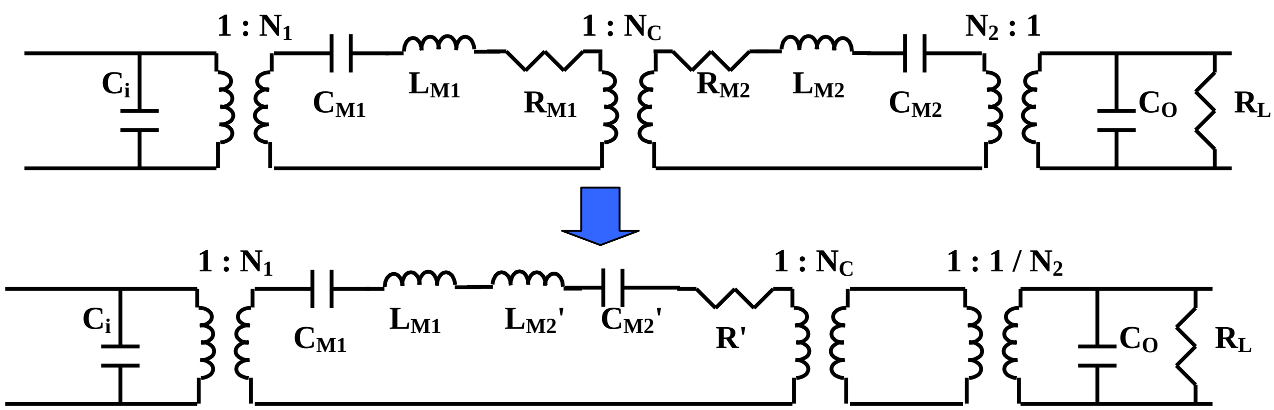
or

$$N_2 = \frac{A\ W}{g_{33}\ d_2}$$

The transformer $1 : N_C$, represents the mechanical coupling between the two halves of the transformer. The stack transformer is tightly coupled and the directions of stress are the same in both halves. This results in $N_C \cong 1$.

Model Simplification:

The response of the transformer can be calculated from this model, but it is possible to simplify the model through a series of simple network conversion and end up in an equivalent circuit whose form is the same as that of a standard magnetic transformer.



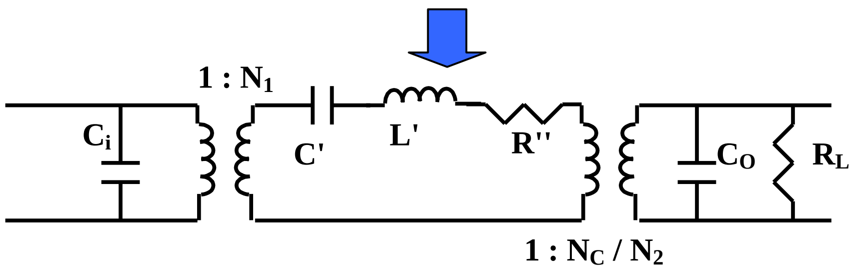
where, due to translation through the transformer,

$$C_{M2}' = N_C^2\, C_{M2} \quad \text{and} \quad L_{M2}' = L_{M2} / N_C^2$$

but $N_C^2 \cong 1$, therefore

$$C_{M2}' = C_{M2} = C_{M1} \quad \text{and} \quad L_{M2}' = L_{M2} = L_{M1}$$

which allows the next level of simplification

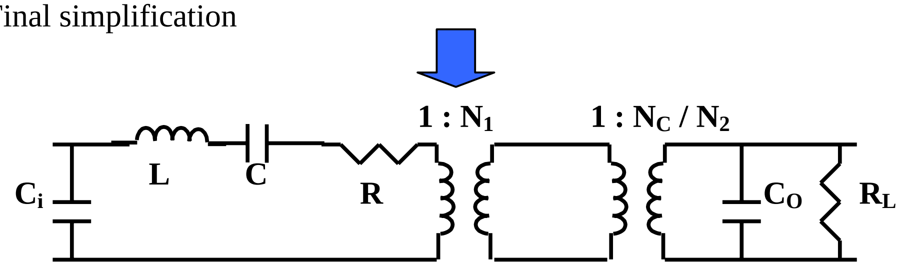


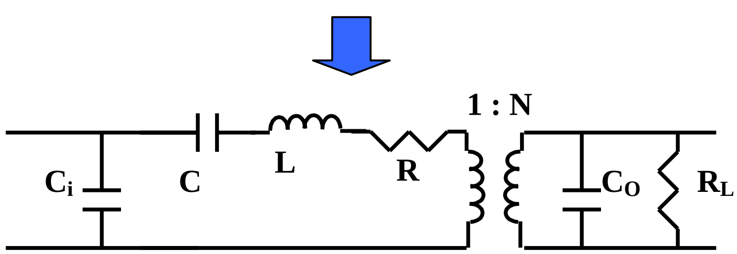
here

$$L' = L_{M1} + L_{M2}' = 2\,L_1 = 2\,\rho\,A\,W\,d_1$$

$$C' = \frac{(C_{M1}\,C_{M2}')}{(C_{M1} + C_{M2}')} = \frac{C_{M1}^2}{2C_{M1}} = \frac{C_{M1}}{2} = \frac{d_1}{2\,A\,W\,Y_{33}}$$

Final simplification





where

$$C = C'\,N_1^2 \quad \text{and} \quad L = L' / N_1^2$$

and, from before

$$N_1 = \frac{A\ W}{g_{33} d_1}$$

therefore

$$C = \frac{d1}{2WLY_{33}} \frac{A^2\ W^2}{g_{33}^2\ d_1^2} = \frac{A\ W}{2Y_{33} g_{33}^2 d_1}$$

$$L = 2\ \rho\ A\ W\ d_1\ \frac{g_{33}^2\ d_1^2}{A^2\ W^2} = \frac{2\ \rho\ g_{33}^2\ d_1^2}{AW}$$

$$N = \frac{N_1\ N_C}{N_2} = \frac{A\ W}{g_{33} d_1} \frac{g_{33} d_2}{A\ W} = \frac{d_2}{d_1}$$

The last value we need to calculate is the motional resistance. This value is based upon the mechanical QM of the material and the acoustic resonant frequency.

Resonate Frequency

$$\omega_O = 1 / \sqrt{L\ C}$$

$$= \frac{1}{\sqrt{\frac{2\ \rho\ d_1\ g_{33}^2}{A\ W} \frac{A\ W}{2Y_{33} g_{33}^2\ d1}}}$$

$$= \frac{1}{\sqrt{\frac{\rho\ d_1^2}{Y33}}} = \frac{1}{d_1 \sqrt{\frac{\rho}{Y_{33}}}}$$

$$c_{PZT} \equiv \text{speed of sound in PZT} = \sqrt{Y\ /\ \rho}$$

therefore

$$\omega_O = c_{PZT}\ /\ d_1$$

The equation shown above states that the resonant frequency is equal to the speed of sound in the material divided by the acoustic length of the device. This is the definition of acoustic resonance and acts as a good check of the model. The final derivation is the value of resistance.

$$Q_M \equiv 1 / \omega_O R C$$

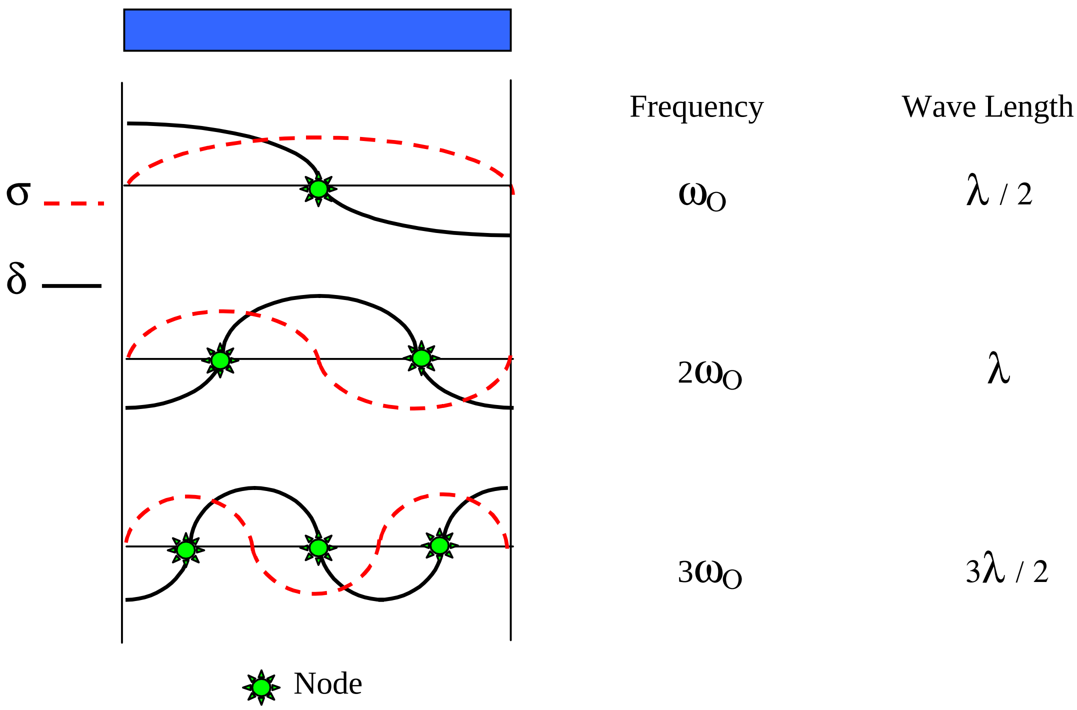
or

$$R = 1 / \omega_O Q_M C$$

$$R = \frac{d_1 \sqrt{\rho / Y_{33}}}{Q_M} \; \frac{2 Y_{33} g_{33}^2 d_1}{A W} = \frac{2 d_1^2 g_{33}^2 \sqrt{\rho Y_{33}}}{Q_M A W}$$

Note: C_M and R are both functions of Y_{33} and Y_{33} is a function of R_L

It should be noted that the model is only valid for transformers driven at or near their fundamental resonate frequencies. This is because the initial mechanical model assumed a single vibration node located at the center of the stack. which is only true when the transformer is driven at fundamental resonance. There are more nodes when the transformer is driven at harmonic frequencies.



Note: Stress is 90^o out of phase from displacement

There are no fixed nodes at frequencies other than resonance. This means that the transformer must be designed with the resonate mode in mind or phase cancellations will occur and there will be little or no voltage gain. It is often difficult to understand the concept of nodes and phase cancellation, so a simple analogy can be used. In this case, waves created in a waterbed will be used to explain the effect.

Pressing on the end of a waterbed creates a "wave" of displacement that travels down the length of the bed until it reaches the opposite end and bounces back. The water pressure (stress) is the lowest, or negative with respect to the water at rest, at a point just in front of the wave and highest at a point just behind the wave. The pressures at the crest and in the trough are at the same pressure as the bed at rest. The wave will reflect back and forth until resistance to flow causes it to dampen out. The average pressure over time at any point in the bed will be exactly the same as the pressure at rest. Similarly, the average stress in a transformer off resonance will approach zero and there will be no net output.

Pressing on the end of the same bed repeatedly just after the wave has traveled down the length, reflected off the end, returned and reflected off the "driven" end will result in a standing wave. This means that one half of the bed is getting thicker as the other half is getting thinner and the center of the bed will be stationary. The center is the node and the thickness plotted over time of either end will form a sine wave. There will be no net pressure difference in the center, but the ends will have a pressure wave which form a sine wave 90^o out of phase with the displacement. The transformer again works in the same manner with no voltage at the node and an AC voltage at the ends. It is fairly simple to expand this concept to harmonics and to other resonate shapes.

Conclusion:

The number of different applications for piezoelectric ceramic, and in particular PZT ceramic, is too great to address in a single paper. The basic principals that have been set forth in this primer can, however, be used to both understand and design piezoelectric structures and devices. The ability to create devices of varying applications and shapes is greatly enhanced by the used of multilayer PZT ceramics.

CTS® WIRELESS COMPONENTS

PZT Piezoelectric Materials

Technical Data (Typical Values)

Property	Symbol	Units	Material Type 3195	3195HD	3203	3203HD
			(Typical Values)			
Dielectric Constant (1KHz)	K_3^T		1800	1900	3250	3800
Dielectric Loss Factor (1KHz)	$\tan\delta_e$	%	1.8	1.8	2.0	2.4
Density	p	g/cm^3	7.7	7.8	7.7	7.8
Curie Point	T_c	°C	350	350	235	225
Mechanical Quality Factor	Q_m		80	80	30	30
Coercive Field*	E_c	KV/cm	14.9	12.0	10.6	8.0
Remanent Polarization	P_r	$\mu Coul/cm^2$	39.2	39.0	37.2	39.0
Coupling Coefficients	K_p		.63	.65	.69	.75
	K_{33}		.70	.72	.73	.75
	K_{31}		.35	.36	.41	.43
	K_t		.49	.48	.53	.55
	K_{15}			.59		.72
Piezoelectric Charge Coefficient (Displacement Coefficient)	d_{31}	$\frac{Coul.}{Newton} \times 10^{-12}$	-175	-190	-275	-320
	d_{33}	(or) $\frac{meters}{volt} \times 10^{-12}$	350	390	550	650
Piezoelectric Voltage Coefficient (Voltage Coefficient)	g_{33}	$\frac{volt\ meters}{Newton} \times 10^{-3}$	24.2	24.0	19.0	19.0
	g_{31}		-11.0	-11.3	-9.6	-9.5
Elastic Modulus	Y_{11}^E	$\frac{Newton}{meter^2} \times 10^{10}$	6.9	6.7	6.3	6.2
	Y_{33}^E		5.5	5.3	5.0	4.9
Frequency Constants Radial	N_r	KHz-cm	202		192	
Resonant Thickness	N_{tr}	KHz-cm	204	211	191	202
Anti-Resonant Thickness	N_{ta}	KHZ-cm	229	236	222	236

Formulas:

Disc Capacitance $= \frac{d^2 \times K_3^T}{5.67 \times t}$ Disc $K_3^T = \frac{5.662 \times c \times t}{d^2}$

Plate Capacitance $= \frac{l \times w \times K_3^T}{4.45 \times t}$ Plate $K_3^T = \frac{4.447 \times c \times t}{l \times w}$

f_r (radial) = Nr/2.54 d

f_r (length) = Nr/2.54 l

f_r (width) = Nr/2.54 w

f_t (thickness) = Nt/2.54 t

Note: Formula length, width, and diameter are for electroded area only.

*Measured at less than 1 Hz.

Definitions

- $\tan\delta_e$ - Dielectric Loss Factor
- p - Mass Density of Ceramic
- T_c - Curie Point
- d_{33} - Direct Charge Coefficient
- d_{31} - Transverse Charge Coefficient
- E_c - Coercive Field
- g_{33} - Direct Voltage Coefficient
- g_{31} - Transverse Voltage Coefficient
- K_p - Planar Electromechanical Coupling Coefficient
- C - Capacitance (nF)
- l - Length (in.)
- w - Width (in.)
- d - Diameter (in.)
- t - Thickness (10^{-3} in.)
- K_{33} - Direct Electromechanical Coupling Coefficient
- K_{31} - Transverse Electromechanical Coupling Coefficient
- K_3^T - Free Dielectric Constant Measured Along Poling Axis
- N_r - Radial Frequency Constant
- N_t - Thickness Mode Frequency Constant
- P_r - Remanent Polarization
- Q_m - Mechancial Q (Quality Factor)
- Y_{33}^E - Direct Youngs Modulus
- Y_{11}^E - Elastic Modulus
- f_r - Resonant Frequency
- f_a - Anti-Resonant Frequency

CTS PZT Piezoelectric Materials, with a fine grain and low porosity microstructure are especially suited for medical ultrasound, ink jet, and other demanding applications. A wide variety of sizes, shapes and metallizations are available, and custom programs are welcome.

Physical and Mechanical Properties

Property	Symbol	Units	3203 HD (PZT Type 5H) Value	3195 HD (PZT Type 5A) Value
Thermal Expansion (Perpendicular to poling)	α	ppm / °C	3.5	3.0
Specific Heat	C_p	J / Kg - °C	420	440
		J/ mol - °C	138	145
Thermal Conductivity	K_d	watts / cm ^{2} - °C	1.9 - 2.3	1.9 - 2.3
		watts / m ^{2} - °K	1.2	1.2
with Au Electrodes		watts / m ^{2} - °K	1.45	1.45
Poisson's Ratio	υ		0.31	0.31
Elastic Constants Short Circuit	S^E_{11}	x 10 $^{-12}$m ^{2} /N	16.6	16.2
	S^E_{33}		21.0	18.6
Elastic Constants Open Circuit	S^D_{11}	x 10 $^{-12}$m ^{2} / N	13.9	14.6
	S^D_{33}		8.8	9.6
Elastic Constants Short Circuit	Y^E_{11}	x 10 $^{-10}$ N / m ^{2}	6.2	6.7
	Y^E_{33}		4.9	5.3
Elastic Constants Open Circuit	Y^D_{11}	x 10 $^{-10}$ N /m ^{2}	7.0	6.8
	Y^D_{33}		11.0	10.6

CTS® WIRELESS COMPONENTS

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CTS Piezoelectric Tweeters

Introduction

Piezo tweeters, in use for 30 years now, offer a quality cost-effective, high-frequency sound source in a rugged, high-efficiency package when used properly. Used improperly, however, they fail to meet their potential. It is the purpose of this article to help the user attain the maximum benefits from pie-zohs, pizzas, pee-zoids, or whatever else they have been called.

Background

Piezoelectricity was discovered by Jacque and Pierre Curie in the late 1880s. They found that certain natural crystals generate an electric field under the influence of a mechanical force. They named the phenomenon piezoelectricity, from the Greek meaning "pressure" electricity. The correct pronunciation is pi e' zo; however, Pe a' zo (the Latin pronunciation) has become as common. Shortly thereafter, it was discovered that this phenomenon is a reversible one. That is, when an electrical field is impressed across the crystal, it undergoes a physical deformation. Since the actual displacements are very small (measured in millionths of an inch), the practical applications for piezoelectricity were slow in coming. The various natural occurring materials were found to be piezoelectric, among them quartz, tourmaline, Rochelle salt, and even wood. The advent of radio resulted in the need for a frequency-stable circuit component. quartz crystals, vibrating at resonance, were found to operate consistently and are still the state of the art in frequency-stable components. This was the first high-volume major application of piezoelectricity.

Underwater warfare in W.W.II generated a need for detection equipment analogous to radar used for planes. It was known that acoustical signals travel extremely well in water, and the first acoustical application for piezoelectricity emerged. A piezoelectric crystal was acoustically coupled to the water through a metal diaphragm. A short burst of energy (ping) caused the crystal to vibrate, setting up and acoustical wave in the ocean. When the wave encountered a hard object, a reflected signal was returned to the sender. Since the piezoelectric device also worked as a receiver, after the initial transmit "ping," it was switched to a receive mode and listened for the returning signal. The time lapse between the transmit and receive was translated directly into distance. Further, by adding multiple receivers aimed in different directions, a direction (bearing) could be determined. Rochelle salt was first used for this application because of its extremely high sensitivity. Unfortunately, it exhibited several temperature and moisture problems that made its use impractical.

A better material was needed. Independent research on both sides of the ocean resulted in a family of synthetic materials that offer high electro-mechanical conversion efficiency with greatly improved temperature and humidity stability characteristics. This synthetic material is actually a ceramic and is processed using methods similar to conventional ceramic sintering techniques. The material is called PZT because it is a polycrystalline lattice structure of the oxides of Lead (P for Pb), Zirconium (Z), and Titanium (T). Since it can be formed using conventional ceramic processes, it offers more design latitude to the transducer engineer than do crystals.

A major difference between PZT and piezo materials found in nature (crystals) is that PZT must be processed further to make it piezoelectric. The microscopic crystallites, known as domains, are in random orientation in the PZT and must be aligned if the material is to be useful. This is done in a process called "poling." A high potential D.C. field is momentarily imposed across the material causing the domains to align themselves with the field. Upon removal of the field, the domains remain aligned (see Figure 1). The poled PZT is now truly piezoelectric and will stay that way unless an excessively high voltage is imposed upon it, or unless it is heated to a very high temperature (Curie point). If either of these conditions is reached, the energy input to the domains exceeds the internal binding force holding the domains in alignment, and the material once again becomes unpoled. This entire process is very much like the magnetizing of a magnet except that we deal with electric fields instead of magnetic fields. It should be noted that the ability of the PZT to retain its polarity is a function of the quality of the material. There are available low quality materials which will de-pole under normal use causing the speaker to gradually lose efficiency (sensitivity). CTS manufactures only the highest grades of PZT.

Theory of Operation

In operation, the domains within a poled PZT wafer (as shown in Figure 2) alter their position slightly when an external field is applied. This causes a slight deformation in the physical geometry of the wafer. When the field is removed, the wafer returns to its original size. These displacements are very small (measured in millionths of an inch) but high in force, and when coupled directly to a liquid or solid medium, are very useful for generating discrete motions. When coupled to air, however, motions of these dimensions are useful only in the ultrasonic region where the acoustic impedance of the air is higher, and provides a better match to the PZT. To provide useful motion in the audio region, a "mechanical lever", or transformer, is required to convert the high-force, low-displacement motion to low-force, high-displacement.

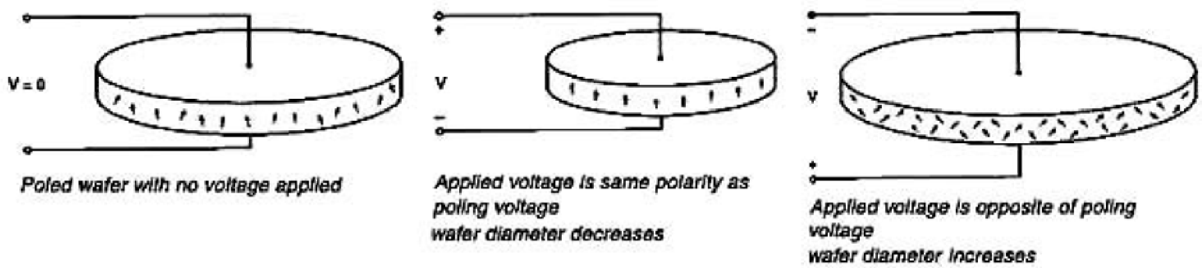


Fig. 2 Dimensional changes of a poled wafer with an applied voltage. The dimensional changes are greatly exagerated for clarity.

This is done by coupling two wafers face-to-face (Figure 3). The wafers are connected such that as one expands, the other contracts. When coupled at their faces with a metal member (centervane), the resulting stress causes the sandwich to dish in and out depending on the amplitude and polarity of the applied signal. This "sandwich" is called a bimorph, as it consists of two active piezo elements.

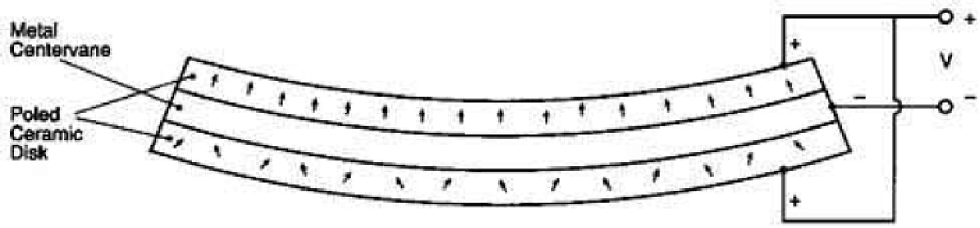


Fig. 3 Cross section of bimorph with applied voltgage

By affixing a cone to the center of the bimorph and anchoring the cone at its periphery, the bimorph vibrates in synchronism with an applied audio signal and pumps the cone for and aft, while pushing against its own mass (Figure 4). This concept, called the "Momentum Drive Principle" was developed and patented by Motorola in 1970. It is the fundamental principle behind a broad family of speakers introduced in the ensuing 20 years through many technical developments and dozens of patents.

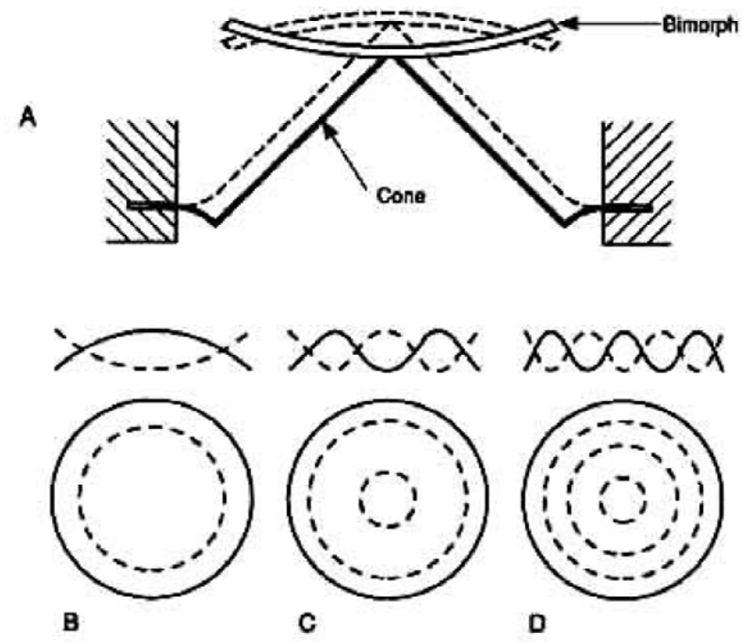
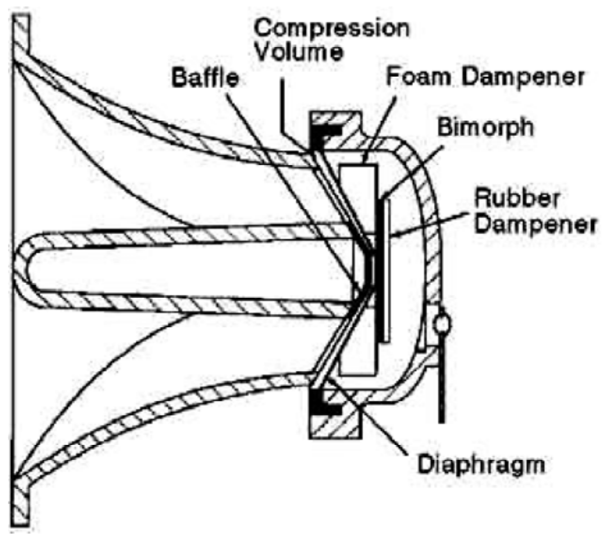


Fig. 4 Momentum drive cone and driver. Principle of piezo driver operation showing: A) momentum driver principle, B) fundamental overtone mode, C) first overtone mode, and D) second overtone mode.

Piezo Tweeter Construction

Let's consider, in detail, the construction of the CTS Super Horn piezo tweeter. Although developed and patented in the early 1970s, it is still a workhorse in commercial sound installations. The circular PZT bimorph in this case consists of two wafers, 0.89" in diameter and 0.0055" thick. The ultra-thin wafer is required to achieve the desired acoustical performance. The bimorph is coupled at it's center to the apex of a specially impregnated diaphragm which then works into a compression volume. Slots in the compression the compression space direct the sound into the throat of the horn. The radial slots are transformed into a 3" circular mouth through the unique shape in the throat of the horn. The actual horn contour is a hybrid design between a pure exponential contour and a hyperbolic one. Again, this computer-generated geometry is optimized for the best acoustical output.



The result is a frequency response (Figure 6) showing high sensitivity and smooth characteristics. Again, it should be noted that low quality products are available on the market using poorly tooled parts and imprecise manufacturing methods. The results are inferior performance and unpredictable results. CTS is proud of its commitment to quality and the consistently high performance of the full line at CTS piezoelectric speakers.

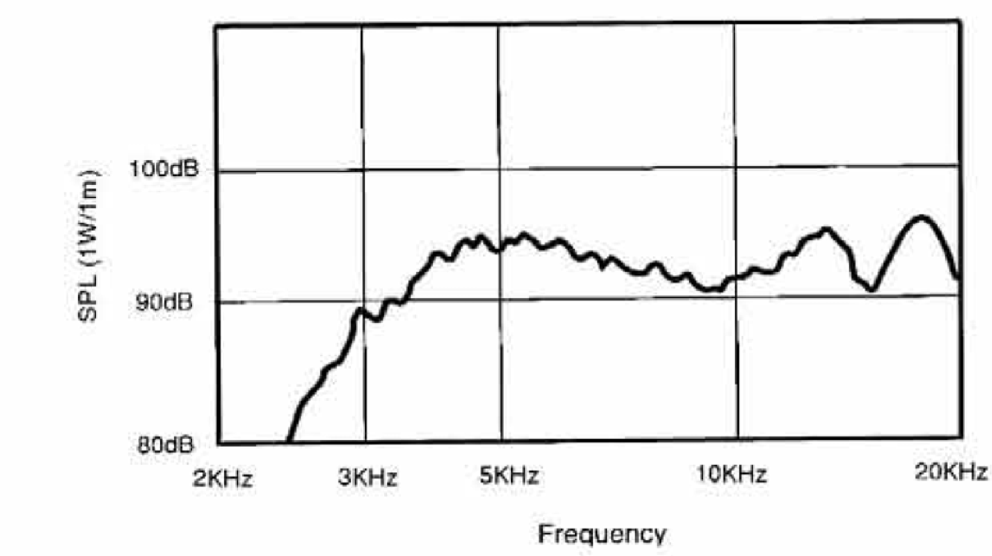


Fig. 6 Super Horn frequency response

Piezo Tweeter Performance

Because of the light dynamic mass of the piezo tweeter (no voice coil, spider, etc.), the response is very fast. Tone burst measurements show the excellent transient response at all frequencies across the band.

A further advantage of the piezo tweeter is its high-power efficiency. With no voice coil, there is no resistive heating and little lost acoustical power. In fact, the actual impedance of the tweeter (Figure 7) is very high, from about 50 ohms to 250 ohms for the Super Horn in its operating range. At these values, the amplifier sees the little additional load from the tweeter, allowing use of arrays with little additional power load. Because it generates little waste energy it is capable of being driven harder than the dynamic tweeter.

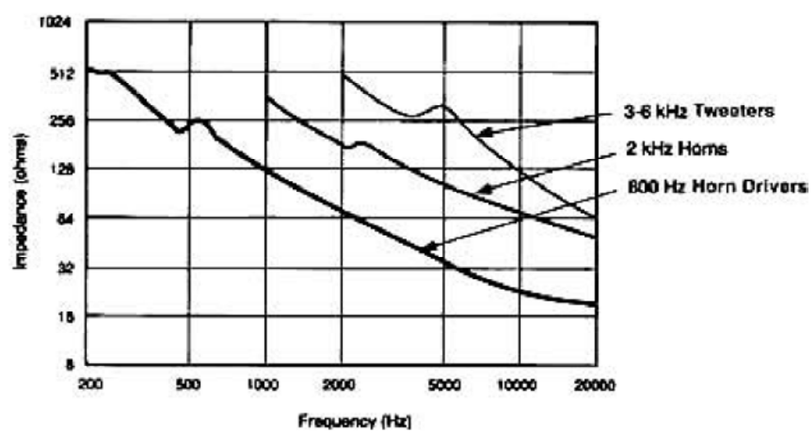


Fig. 7 Piezo speaker impedance

Application Hints

With all the aforementioned virtues of piezo tweeters, there are still some issues in their use with which the design engineer should be familiar.

The piezo tweeter appears like a lossy capacitor to the amplifier (Figure 8). As shown in the impedance plot (Figure 7) the impedance decreases with frequency. Many amplifiers today boast outputs that extend to 100 kHz. At those frequencies, ultrasonic resonances may occur between the amplifier and the tweeter, causing damage to one or the other or both.

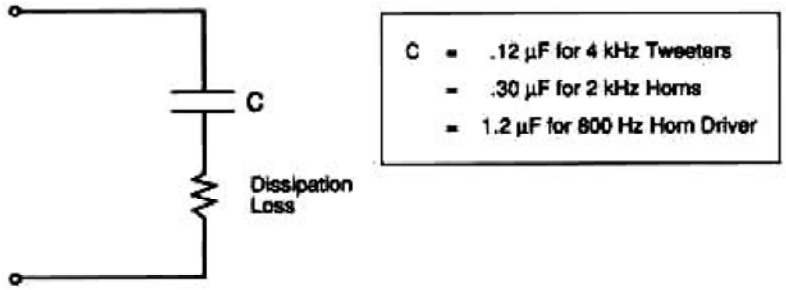
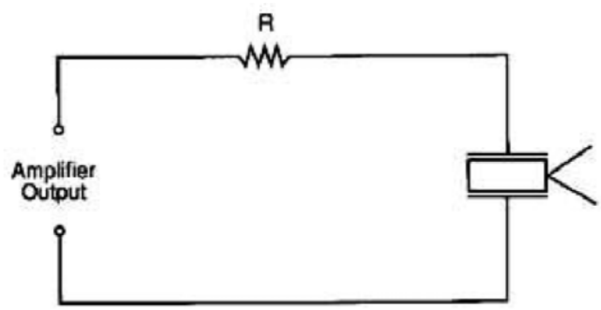


Fig. 8 Piezo tweeter equivalent circuit

If such an amplifier is used, particularly with an array of tweeters, a small series resistor is suggested (Figure 9). For CTS tweeters with a low-end cutoff of 3 kHz to 6 kHz, a 50 ohm, 2 watt resistor wired in series with each tweeter will prevent this resonance problem without noticeably affecting the response. It should be noted that this problem is uncommon in automotive applications since these amplifiers usually roll off at 20 kHz. The 2 kHz horn products do not require an external series resistor since one is built into each unit. The KSN1086 mid-range driver and KSN1090 and 1103 voice range products should be protected with a 20 ohm, 10 watt series resistor.



Speaker Family	R
3-6 kHz Tweeters	50 Ω 2W
2 kHz Horn	Not Required
800 Hz Horn Driver	20 Ω 10W

Fig.9 Protective series resistor

Crossover Networks

The piezo tweeter does not require a crossover network. Since the tweeter is capacitive in nature, it rejects low-frequency power. However, if the mid-range is still operating at the turn-on of the tweeter (4 kHz in the case of the Super Horn), a harshness may be heard in the total system. This disturbance in the crossover region can be minimized by the addition of an R-C filter (Figure 10) tuned to attenuate the turn-on peak, rolling off the mid-range a little earlier.

If a conventional crossover network is to be used, the tweeter must be made to look "resistive" in order to work with the crossover. This can be done by wiring an 8 ohm resistor /across/ the piezo tweeter. It should be noted, however, that the power efficiency benefits are now lost since the piezo tweeter will look more like an 8 ohm dynamic unit electrically. It will, however, allow the use of conventional crossover technology. If a variable level attenuation is desired, an L-Pad can be used.

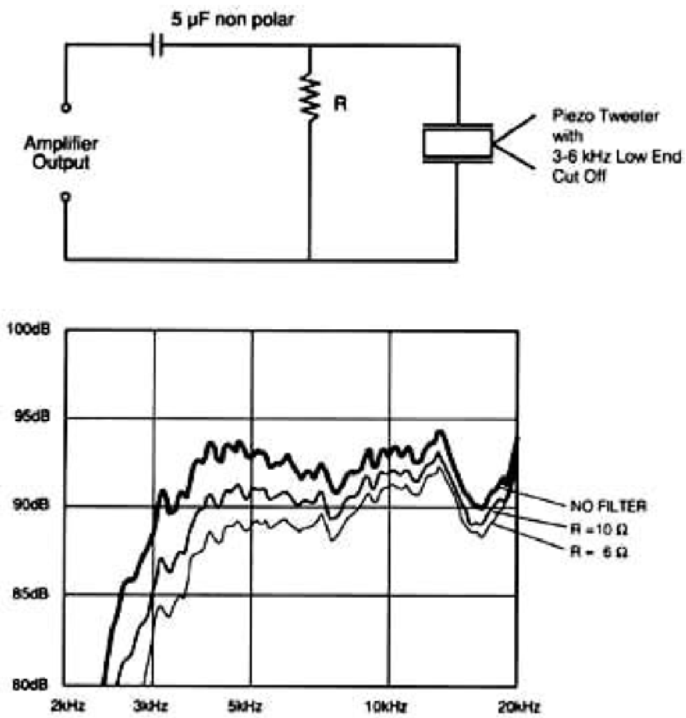
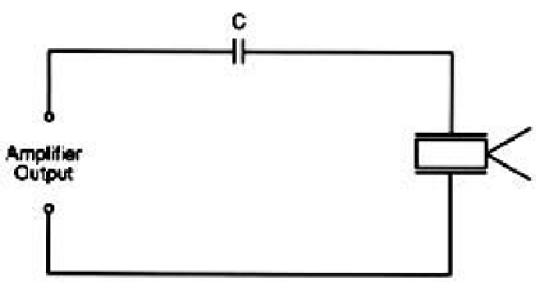


Fig. 10 Single stage R-C filter for attenuating turn on response

If a straight level attenuation is desired, a simple (non-polar) capacitor (Figure 11) can be series wired.



	C	Attenuation
3 - 6 kHz Tweeters	.1 µF	6 db
	.04 µF	12 dB
2 kHz Horns	.3 µF	6 dB
	.12 µF	12 dB

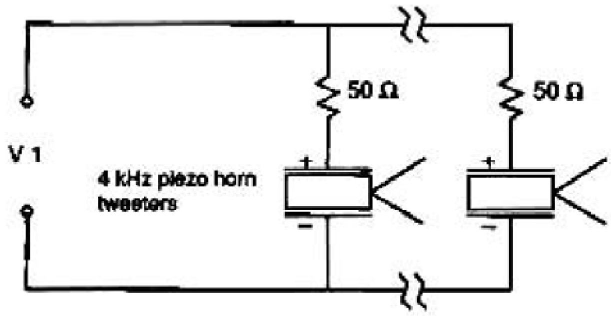
Fig. 11 Series attenuating capacitor

Multiple Tweeters

System sensitivity can be increased by adding piezo tweeters in parallel (Figure 12). The high electrical impedance of CTS' piezo tweeters allows several units to be connected in parallel without overloading the amplifier.

Each time the number of tweeters connected in parallel is doubled, the average sensitivity for the array increases by 3 to 6 dB. The actual increase depends on factors such as off-axis angle, frequency, tweeter model and the configuration of the array. For CTS Super Horns, the on-axis response increases 6 dB for each doubling. Part of this increase occurs because of the narrower beam produced by multiple horns. As the beam becomes narrower, the off-axis response degrades as a result of destructive interference between tweeters. The angle at which the destructive interference is the greatest depends on the frequency and on the spacing between the tweeters.

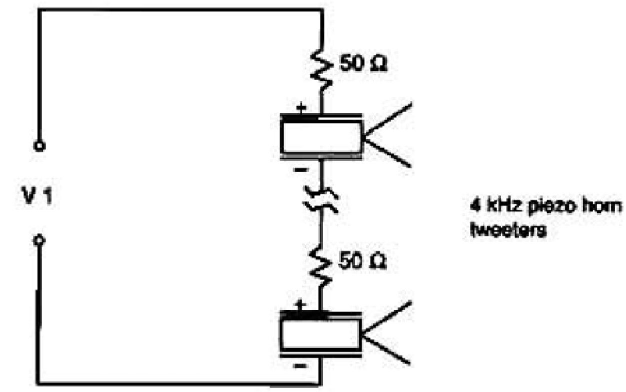
The destructive interference can be minimized in one plane by orienting a single row or column perpendicular to that plane. For example, if horizontal dispersion is more important than vertical, the tweeters should be mounted in a single vertical column. This assures that the horizontal dispersion of the array is identical to that of a single tweeter. The vertical dispersion, however, can begin to degrade significantly beyond 5 degrees. Mounting the tweeters at an angle (off-axis) with respect to one another can also improve the off-axis response.



Number of tweeters connected in parallel	Average sensitivity change change (dB)	On axis sensitivity change (dB)
1	0 (ref)	0 (ref)
2	+3	+6
3	+5	+10
4	+6	+12
8	+9	+18

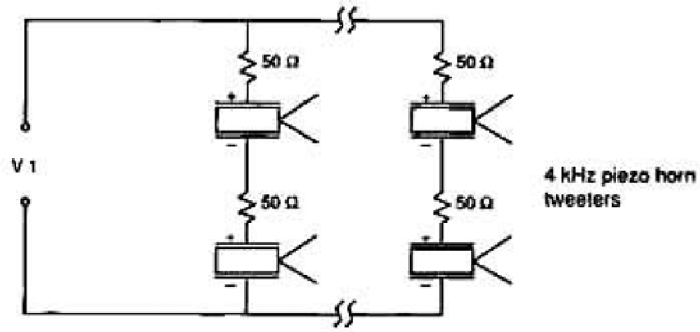
Fig. 12 Output level increase for parallel connected piezo tweeters

Connecting piezoelectric tweeters in series doesn't increase system sensitivity, but it does higher sound pressure levels at maximum rated power (Figure 13). maximum power handling capability of the array increases as tweeters are added in series. At maximum rated drive level, doubling the number of tweeters in series reduces the voltage across each tweeter by half with the resulting SPL decrease of 6 dB for each tweeter. The additional tweeters, however, create a 6 dB increase for a net on-axis sensitivity change of 0 dB. If the voltage applied to the array is now doubled, so that each tweeter sees it's maximum rated voltage, the array's on-axis SPL increases 6 dB.



Number of tweeters connected in series	Average sensitivity change (dB)	On axis sensitivity change (dB)	On axis SPL at max. power rating (dB)	Max. array EIA voltage (V1 rms volts)	Max. array EIA power (watts ref. to 8 ohms)
1	0 (ref)	0 (ref)	0 (ref)	25	75
2	-3	0	+6	50	300
3	-5	0	+10	75	700
4	-6	0	+12	100	1250

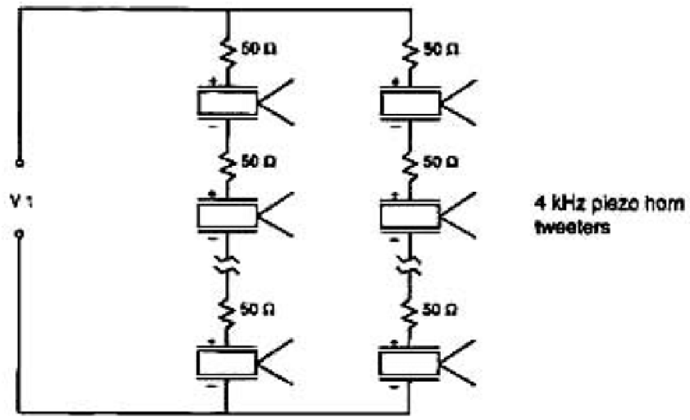
Fig. 13 Output level for series connected piezo tweeters



Number of pairs connected	Average sensitivity change (dB)	On axis sensitivity change (dB)	On axis SPL at max. EIA rated power (dB)
1	-3	+3	+9
2	0	+6	+12
4	+3	+9	+15
8	+6	+12	+18

Maximum EIA rated voltage for this array is 50 volts rms which is equivalent to 300 watts referenced to 8 ohms

Fig. 14 Output level for parallel connected, series pairs of piezo tweeters



Total number of tweeters connected	Average sensitivity change (dB)	On axis sensitivity change (dB)	On axis SPL at max. EIA rated power (dB)	Max. array EIA voltage (V1 rms volts)	Max. array EIA power (watts rel. to 8 ohms)
1	0 (ref)	0 (ref)	0 (ref)	25	75
2	-3	+6	+6	25	75
4	0	+6	+12	50	300
8	-3	+6	+18	100	1250

Fig. 15 Output level for two strings of series connected Piezo Tweeters

Power Handling

The power rating of CTS piezoelectric speakers is determined using the EIA RS426 test method. This is a continuous 8 hour noise test with peak voltage spikes twice (4 times higher in terms of power) the average applied signal. Thus, for a speaker to be rated at 75 watts (25 volts), it must not degrade after 8 hours of continuous operation at 75 watts with 300 watt spikes. As a result of using the EIA test method, CTS power ratings for its piezoelectric speakers tend to be conservative compared to conventional industry claims for speaker systems. In addition, the extremely dense, high-quality ceramic manufactured by CTS withstands cracking and other high power failure mechanisms much better than the piezoelectric ceramic used by many other manufacturers.

Powerline Series

The Powerline series of 2 kHz horns use an internal protection circuit which allows the horn to continuously handle the full output of a 400 watt (8 ohm reference) amplifier.

The protector is a parallel combination of a miniature light bulb and a positive temperature coefficient resistor (PTC)(Figure 16).

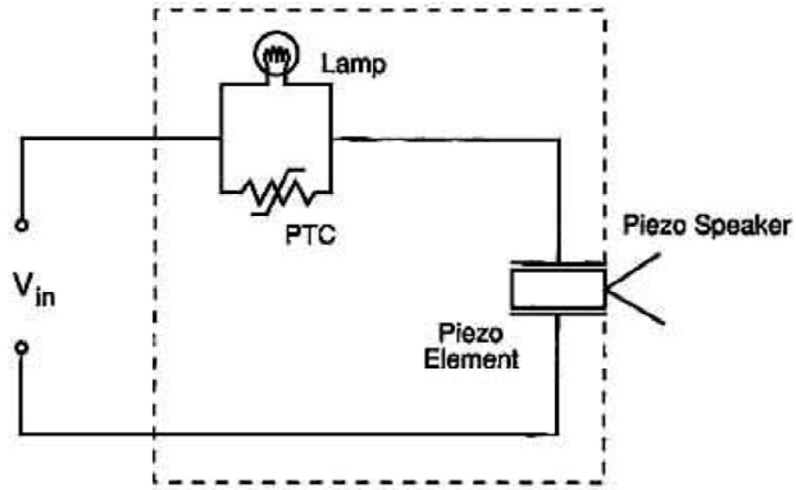


Fig. 16 Powerline internal protection circuit

In a music system in which there is excessive clipping at high power, or high-amplitude high-frequency signal content, the piezo drive element sees very large currents and will heat up due to dissipation losses. When the PTC senses the high temperature it increases its resistance dramatically. This has the immediate effect of significantly lowering the power into the driver, and the SPL produced. To avoid this sudden shift, and make the power control practically imperceptible, the miniature lamp is wired in parallel with the PTC. The lamp is essentially a very fact-acting PTC and responds to music peaks rather than RMS heating as does the PTC. The audible effect is similar to that produced by a level compressor. In this way, the driver is held below damaging levels.

The resulting speaker performance then is as follows: under normal operating conditions, the powerline speaker performs in it's normal mode, faithfully reproducing the signal applied in proportion to its volume. Under temporary, extremely high power surges (even in excess of 400 watts), the speaker will still perform in its normal expected mode. But now, if subjected to continuous high-frequency power, above 100 watts or so, the PTC temporarily opens up, allowing the speaker to continue to play, drawing its power through the light bulb, at a somewhat compressed power level. The transition is smooth, and at the power levels being played at the time, barely perceptible to the human ear. When the speaker cools off, the PTC automatically resets, and conditions return to normal.

Conclusion

The CTS product line of piezo tweeters has grown dramatically since the Super Horn made its debut 18 years ago. CTS' speaker portfolio now includes mid-range drivers, voice range products, 2 kHz horns, and the Power Line family. CTS is committed to total customer satisfaction. With the wide variety of models available, and the technical tips provided herein, we are confident we can satisfy your audio design needs.

CTS Piezoelectric Speakers

Horn Tweeters

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1001A, 1005A 	Superhorn KSN1001A - Recessed mount KSN1005A - Flush mount	3.4 x 3.4 in. 85 x 85 mm	4-30	94	100
KSN1056A 	Exponential Horn	3.8 in. dia. 95 mm dia.	3.5-30	92	100
KSN1016B, 1168B 	Wide Dispersion Horn 2 x 5	5.7 x 2.6 in. 145 x 67mm	4-30	92	100
KSN1025B 	Wide Dispersion Horn 2 x 6	7.4 x 3.1 in. 187 x 79 mm	1.8-30	92	75
KSN1141B 	Wide Dispersion 2 x 6 with protection	7.4 x 3.1 in. 187 x 79 mm	1.8-30	92	Protected to 400
KSN1176A 	Low Cost 2 x 6	7.4 x 3.1 in. 187 x 79 mm	3.5-30.	92	75

KSN1165A 	Bullet Tweeter	4.3 x 4.3 in. 110 x 110mm	1.8-30.	92	Protected to 400
KSN1177A 	Twin Drive	6.4 x 3.8 in. 161 x 95 mm	3.5-20	99	100
KSN1167A 	Bullet Tweeter	3.5 x 3.5 in. 87 x 87 mm	3.5-30.	94	100

Cone Tweeters

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1075A 	1.5 inch	1.6 in. dia. 41 mm	6-50	88	50
KSN1020A 	2 inch	2.0 in. dia. 51 mm dia.	6-50	89	50
KSN1036A 	3.75 inch	3.8 in. dia. 95 mm dia.	3-40	90	75
KSN1139A 	Dome Tweeter	2.0 x 2.0 in. 51 x 51 mm	6-20	90	50

Horns

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1151A 	CD Horn (no driver)	10.5 x 4.4 in. 267 x 112 mm			
KSN1196A 	Exponential Horn (no driver)	15.0 x 5.0 in. 381 x 127 mm			

Horn Drivers

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1197A 	Driver w Threaded Adaptor	2.0 in. dia. 50 mm dia.	3.5-40	92	100
KSN1142A 	Driver w Threaded Adaptor	2.5 in. dia. 64 mm dia.	1.8-30	92	Protected to 400
KSN1188A 	Midrange Driver	4.0 in. dia. 102 mm dia	0.8-20	92	100

Alarms

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1152A 	High Output Alarm	2.4 in. dia. 60 mm dia.	2-4	112@1ft., 12Vp-p	
KSN1204A 	High Output Alarm	1.8 in. dia. 46 mm dia.	2.2-4	110@1ft., 12Vp-p	
KSN1212A 	KSN1204A w conformal coating	1.8 in. dia. 46 mm dia.	2.2-4	110@1ft., 12Vp-p	

Voice Range Speaker

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1090A, 1103A 	Low Profile, Non Magnetic KSN1090A - Standard KSN1103A - Harsh Environments	3.8 in. dia. 95 mm dia.	0.5-20	82	50

Surface Mount

Product	Description	Size	Frequency Response KHz	Sensitivity 2.83, 1m db	Power EIA RS426 Watts
KSN1192A, 1193A 	Auto Surface Mount Tweeter KSN1192A - Bulk packed KSN1193A - Matched pairs	2.0 in. dia. 51 mm dia.	5-30	88	50