Piezo Source

PIEZOELECTRIC SPEAKER

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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 electro strictive 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 electro strictive 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 x 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:

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

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}:

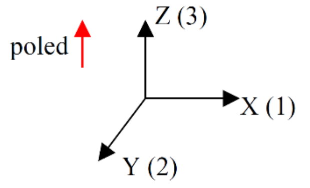
$$\begin{aligned} D_1 &= \boxed{\varepsilon_{11}\,E_1} + \varepsilon_{12}\,E_2 + \varepsilon_{13}\,E_3 \\ D_2 &= \varepsilon_{21}\,E_1 + \boxed{\varepsilon_{22}\,E_2} + \varepsilon_{23}\,E_3 \\ D_3 &= \varepsilon_{31}\,E_1 + \varepsilon_{32}\,E_2 + \boxed{\varepsilon_{33}\,E_3} \end{aligned}$$

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 (Kilograms)
Z	Impedance	Z_M	Mechanical Impedance
$i = \frac{dQ}{dt}$		$v = \frac{ds}{dt}$	
$e = L\frac{di}{dt} = L\frac{d^2i}{dt^2}$		$f = M\frac{dv}{dt} = M\frac{d^2s}{dt^2}$	

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

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

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.

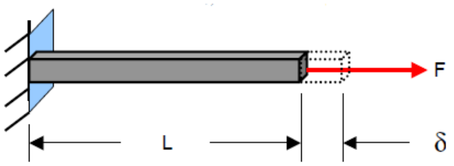
Elastic Modulus (Young's Modules)

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

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

Stress = $\sigma = F / A$
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 = Electric Displacement (or Charge Density)

d_{ij} = 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.

$$D_i = \frac{\sigma_j \lambda_j}{E_j}$$

Earlier, electric displacement was defined as

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

therefore,

$$e_{ij}\ E_j = dij\ \sigma$$

and

$$E_j = \frac{d_{ij}}{\varepsilon_{ij}} \sigma$$

which results in a new constant

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

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:

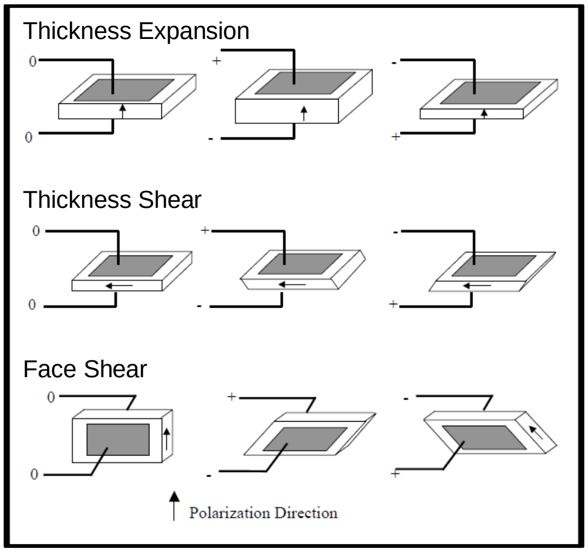
$$g = \frac{\text{field}}{\text{stress}} = \frac{\text{volts/meter}}{\text{newtons/meter squared}} = \frac{\Delta L/L}{\varepsilon V/t}$$

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



Poling

Piezoelectric ceramic materials, as stated earlier, 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 permanently increases in dimension between the poling electrodes and decreases in dimensions parallel to the electrodes. The material can be depoled 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:

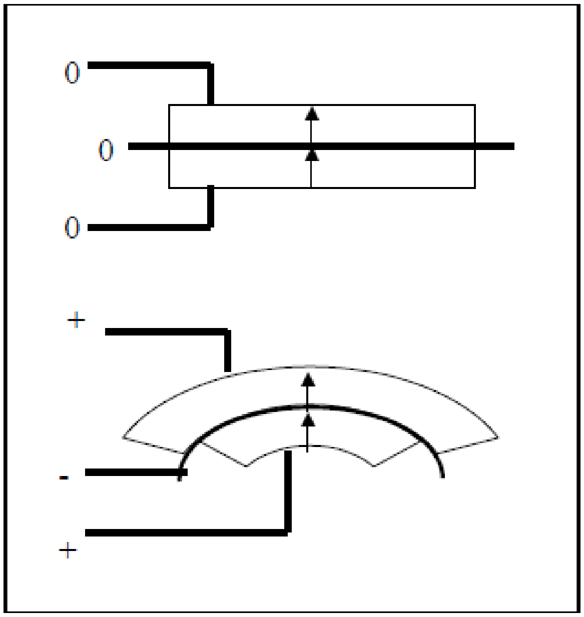
Applying a compressive force in the direction of poling (perpendicular to the poling electrodes) or a tensile force parallel to the poling direction results in a voltage generated on the electrodes which has the same polarity as the original poling voltage. A tensile force applied perpendicular to the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

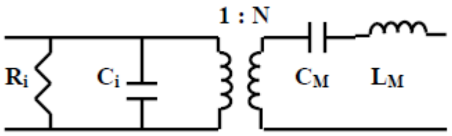
Mechanical Loss:

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

Electrical Loss:

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

Simplified Piezoelectric Element Equivalent Circuit



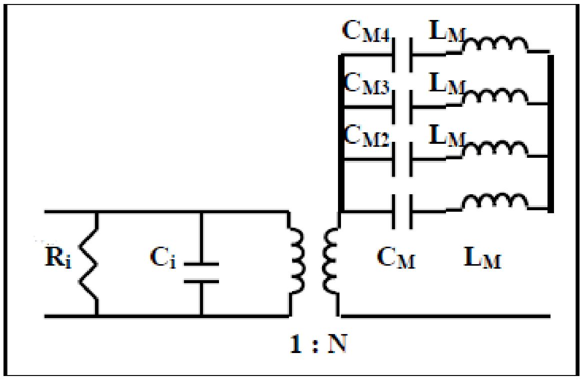
R_i = Electrical Resistance
C_i = Input Capacitance

$$= \frac{\varepsilon_0\,\varepsilon_r\,A}{t}$$

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)

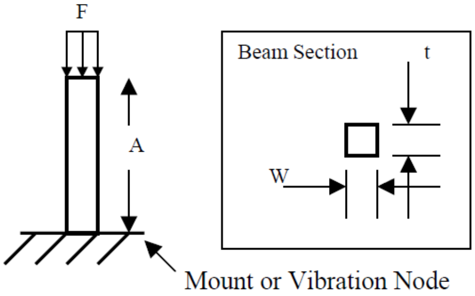
This model has been simplified and it is missing several factors. It is only valid up to and slightly beyond resonance. The first major problem with the model is related to the mechanical compliance (C_M). Compliance is a function of mounting, shape, deformation mode (thickness, free bend, cantilever, 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.

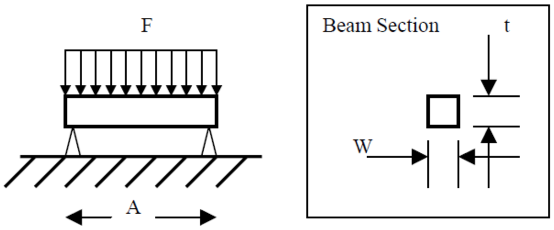
Simple Beam - Uniform End Load



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

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

Simple Beam - Uniform Load - End Mounts



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

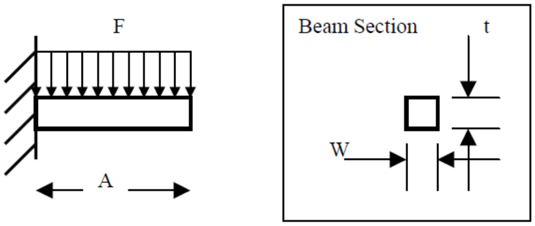
where I is the moment of inertia

$$I = \frac{W\,t^3}{12}$$

therefore

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

Simple Beam - Uniform Load - Cantilever Mount

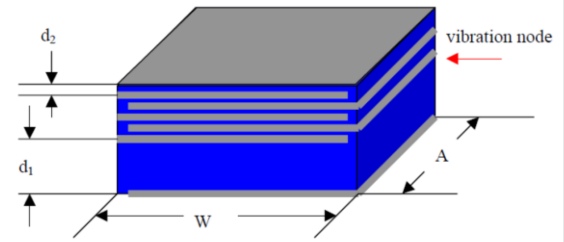


$$C_M = \frac{A^3}{8\,Y_{ij}\,I} = \frac{3}{2}\frac{A^3}{Y_{ij}\,W\,t^3}$$

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.

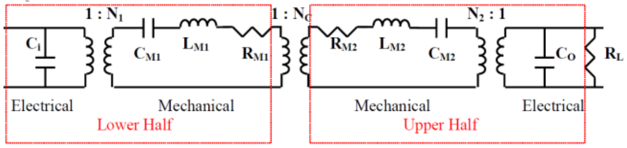
Simple Stack Piezoelectric Transformer

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.



n = number of thin layers
$nd_2 = d_1$

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, Ri, and the output resistance, RO, 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

$$C_i = \varepsilon_0\,\varepsilon_r\,\frac{\text{Input Area}}{\text{Input Thickness}} = \varepsilon_0\,\varepsilon_r\,\frac{A\,W}{d_1}$$

similarly,

$$C_i = \varepsilon_0\,\varepsilon_r\,\frac{\text{Output Area}}{\text{Output Thickness}} = \varepsilon_0\,\varepsilon_r\,\frac{n\,A\,W}{d_2}$$

Mechanical Compliance

The mechanical compliance, CM, 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.

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

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

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

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 QM and Q of the material at resonance and will be calculated later.

Ideal Transformer Ratio

The transformer ratio, N1, 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 from the piezoelectric constant, g.

as before

$$g = \frac{\text{Electric Field}}{\text{Stress}} = \frac{\text{volts/meter}}{\text{newtons/meter squared}}$$

therefore

$$\frac{1}{g} = \frac{\text{N/m}}{\text{V/m}^2}$$

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 N1. 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.

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

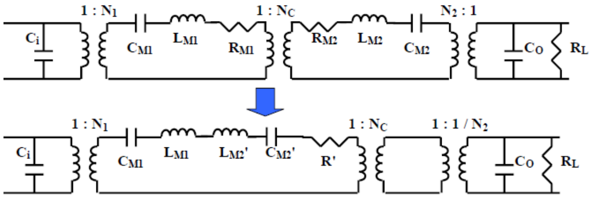
or

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

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,

$$C_{M2}' = N_C^2\,C_{M2}$$

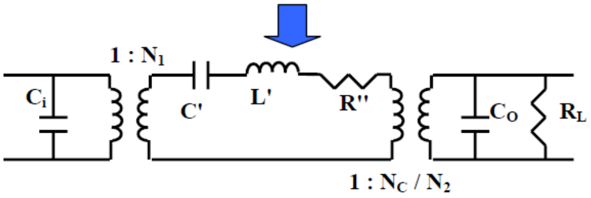
$$L_{M2}' = L_{M2} / N_C^2$$

but $N_C^2 \cong 1$, therefore

$$C_{M2}' = C_{M2} = C_{M1}$$

$$L_{M2}' = L_{M2} = L_{M1}$$

which allows the next level of simplification

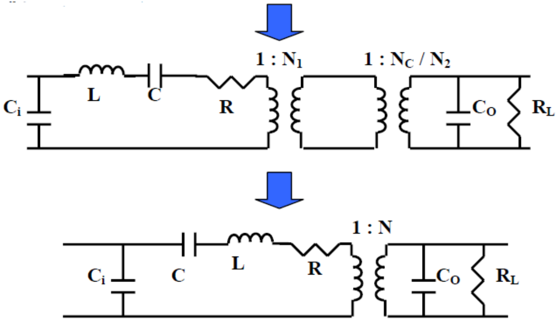


here

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

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

Final Simplification



where

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

therefore

$$C = \frac{d_1}{2\,W\,L\,Y_{33}}\,\frac{A^2\,W^2}{{g_{33}}^2\,{d_1}^2} = \frac{A\,W}{2\,Y_{33}\,{g_{33}}^2\,d_1}$$

$$L = 2\,\rho\,A\,W\,d_1\,\frac{{g_{33}}^2\,{d_1}^2}{A^2\,W^2} = \frac{2\,\rho\,{g_{33}}^2\,{d_1}^3}{A\,W}$$

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

Resonant Frequency

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.

$$\omega_0 = \frac{1}{\sqrt{L\,C}}$$

$$= \frac{1}{\sqrt{\frac{2\,\rho\,{g_{33}}^2\,{d_1}^3}{A\,W}\,\frac{A\,W}{2\,Y_{33}\,{g_{33}}^2\,d_1}}}$$

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

$$\omega_0 = \frac{1}{d_1\sqrt{\frac{\rho}{Y_{33}}}}$$

speed of sound in PZT

$$c_{PZT} = \sqrt{\frac{Y}{\rho}}$$

therefore

$$\omega_0 = \frac{c_{PZT}}{d_1}$$

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.

$$Q_M = \frac{1}{\omega_0 \, R \, C}$$

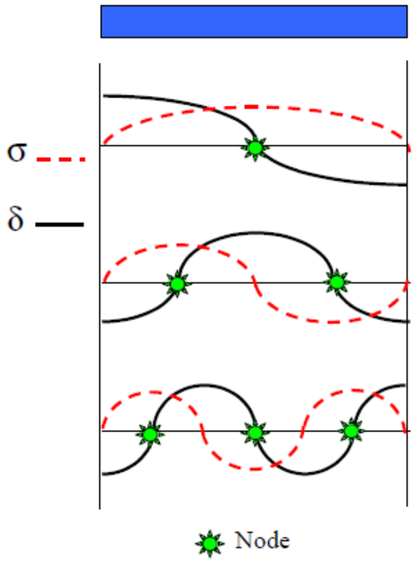
or

$$R = \frac{1}{\omega_0 \, Q_M \, C} = \frac{d_1 \sqrt{\rho / Y_{33}}}{Q_M} \, \frac{2 \, Y_{33} \, g_{33}{}^2 \, d_1}{A \, W}$$

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

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.



Frequency	*Wave Length*
ω_0	*$\lambda / 2$*
$2\omega_0$	*λ*
$3\omega_0$	*$3\lambda / 2$*

Note: Stress is 90° 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 90o 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 principles 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.

PZT Piezoelectric Materials

Technical Data (Typical Values)

Property	Symbol	Units	Material Type		*(Typical Values)*	
			3195	**3195HD**	**3203**	**3203HD**
Dielectric Constant (1KHz)	K^T_3		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 (Measured at < 1Hz)	E_c	KV/cm	14.9	12.0	10.6	8.0
Remanent Polarization	P_r	µC/cm^2	39.2	39.0	37.2	39.0
Coupling Coefficients	K_p		0.63	0.65	0.69	0.75
	K_{33}		0.70	0.72	0.73	0.75
	K_{31}		0.35	0.36	0.41	0.43
	K_t		0.49	0.48	0.53	0.55
	K_{15}			0.59		0.72
Piezoelectric Charge Coefficient (Displacement Coefficient)	d_{31}	C/N x 10^{-12} or m/V x 10^{-12}	-175	-190	-275	-320
	d_{33}		350	390	550	650
Piezoelectric Voltage Coefficient (Voltage Coefficient)	g_{33}	V-m/N x 10^{-3}	24.2	24.0	19.0	19.0
	g_{31}		-11.0	-11.3	-9.6	-9.5
Elastic Modulus	Y^E_{11}	N/m^2 x 10^{10}	6.9	6.7	6.3	6.2
	Y^E_{33}		5.5	5.3	5.0	4.9
Frequency Constants Radial	N_r	KHz-cm	202		192	
Resonant Thickness	N_{tr}		204	211	191	202
Anti-Resonant Thickness	N_{ta}		229	236	222	236

Formulas

$$\text{Disc Capacitance} = \frac{d^2 \text{ x } K^T_3}{5.67 \text{ x } t} \qquad \text{Disc } K^T_3 = \frac{5.662 \text{ x } c \text{ x } t}{d^2}$$

$$\text{Plate Capacitance} = \frac{l \text{ x } w \text{ x } K^T_3}{4.45 \text{ x } t} \qquad \text{Plate } K^T_3 = \frac{5.662 \text{ x } c \text{ x } t}{l \text{ x } w}$$

For electrode:

f_r (radial) = Nr/2.54 d
f_r (length) = Nr/2.54 l
f_r (width) = Nr/2.54 w
f_r (thickness) = Nt/2.54 t

Definitions

$\tan\delta_e$ - Dielectric Loss Factor
p - Mass Density of Ceramic
T_c - Curie Point

C - Capacitance (nF)
l - Length (in.)
w - Width (in.)

N_r - Radial Frequency Constant
N_t - Thickness Mode Frequency Constant
P_r - Remanent Polarization

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

d - Diameter (in.)
t - Thickness (10^{-3} in.)
K_{33} - Direct Electromechanical Coupling Coefficient
K_{31} - Transverse Electromechanical Coupling Coefficient
K^T_3 - Free Dielectric Constant Measured Along Poling Axis

Q_m - Mechanical Q (Quality Factor
Y^E_{33} - Direct Youngs Modulus
Y^E_{11} - Elastic Modulus
f_r - Resonant Frequency
f_a - Anti-resonant Frequency

Piezo Source 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 J/mol- °C	420	440
Thermal Conductivity with Au Electrodes	K_d	watts/cm^2-°C watts/m^2-K watts/m^2-K	138 1.2 1.45	145 1.2 1.45
Poisson's Ratio	v		0.31	0.31
Electric Constants Open Circuit	S^E_{11} S^E_{33}	x 10^{-12} m^2/N	16.6 21.0	16.2 18.6
Electric Constants Open Circuit	S^D_{11} S^D_{33}	x 10^{-12} m^2/N	13.9 8.8	14.6 9.6
Electric Constants Short Circuit	Y^E_{11} Y^E_{33}	x 10^{-10} N/m^2	6.2 4.9	6.7 5.3
Electric Constants Open Circuit	Y^D_{11} Y^D_{33}	x 10^{-10} N/m^2	7.0 11.0	6.8 10.6

Piezo Source
Piezoelectric Tweeters

Piezo tweeters, developed and patented in the early 1970s, offer a quality cost-effective, crisp high-frequency sound source in a rugged, high-efficiency great for high-volume music play back. This article will help the user optimize the benefits of Piezo Source, Inc. products.

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 piezoelectric materials found were:

- Quartz
- Tourmaline
- Rochelle Salt
- 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.

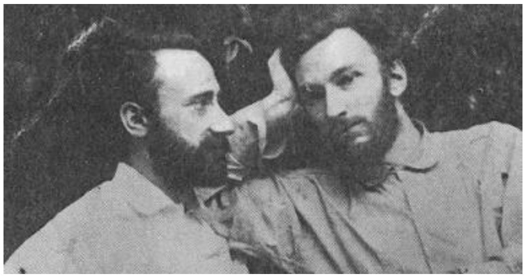


Fig 1 Jacque and Pierre Curie

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.

1. A piezoelectric crystal was acoustically coupled to the water through a metal diaphragm.
2. A short burst of energy (ping) caused the crystal to vibrate, setting up and acoustical wave in the ocean.
3. When the wave encountered a hard object, a reflected signal was returned to the sender.
4. 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.
5. The time lapse between the transmit and receive was translated directly into distance.
6. 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)
- 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. The poled PZT is now truly piezoelectric and will stay that way unless:

- excessively high voltage is imposed upon it
- 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). Piezo Source 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.

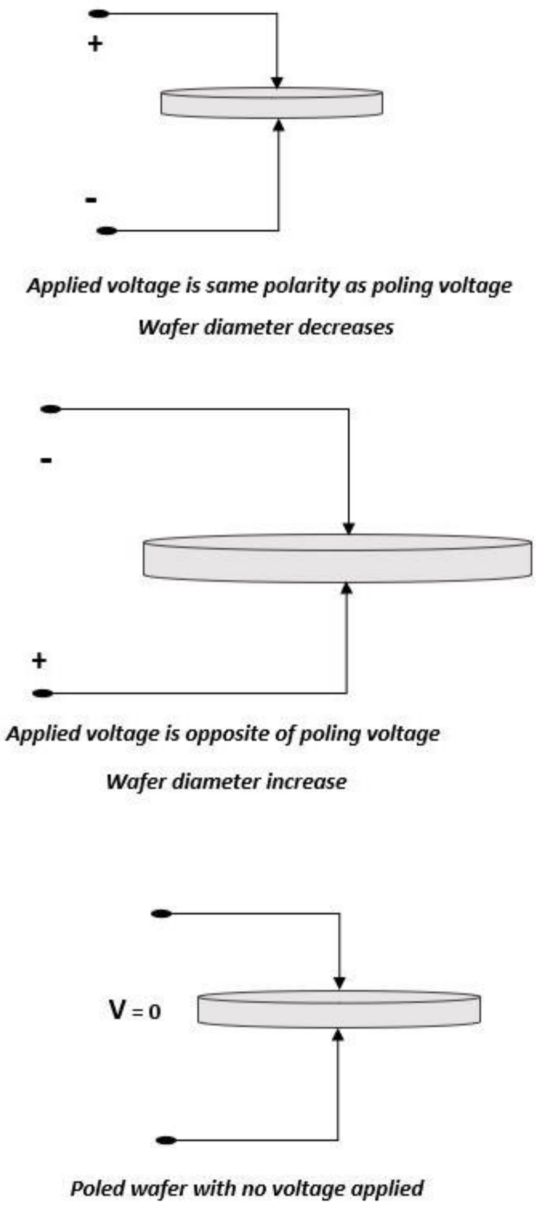


Fig. 2 Dimensional changes of a poled wafer with an applied voltage. The dimensional changes are greatly exaggerated for clarity

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.

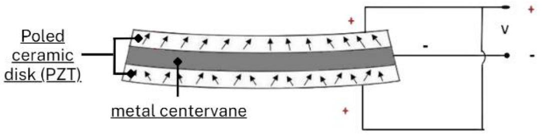


Fig. 3 Cross section of bimorph with applied voltage

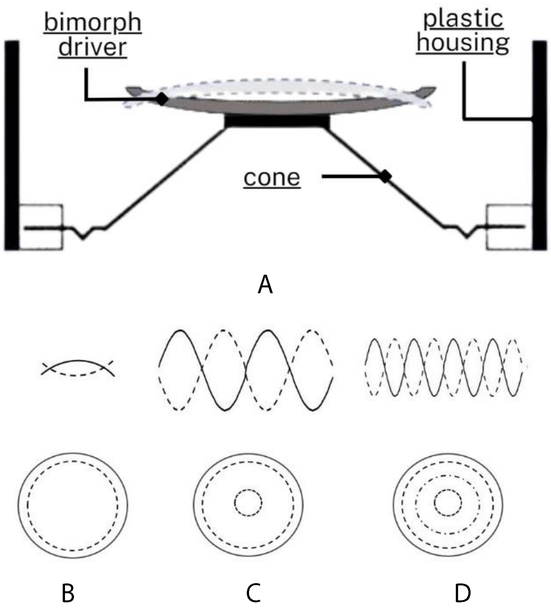


Fig. 4 Momentum drive cone and driver. Principle of piezo driver operation showing A) momentum driver principle, B) fundamental overtone mode, C) first overtone mode, and D) second overtone mode.

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 fore 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.

Piezo Tweeter Construction

Let's consider, in detail, the construction of the Piezo Source 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 its 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.

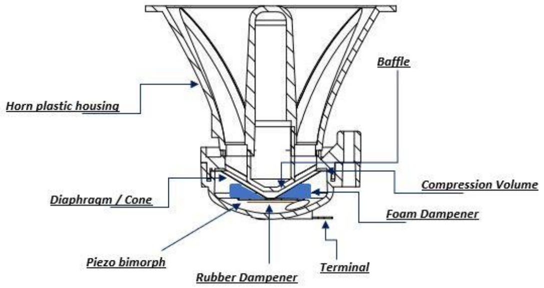


Fig. 5 Cross-section of a piezo tweeter

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.

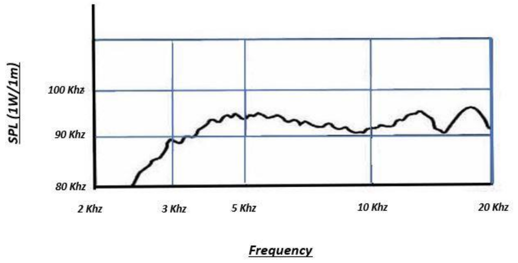


Fig. 6 Super Horn frequency response

Piezo Source is proud of its commitment to quality and the consistently high performance of the full line at Piezo Source piezoelectric speakers.

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.

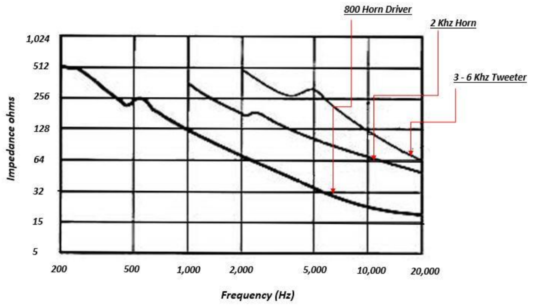
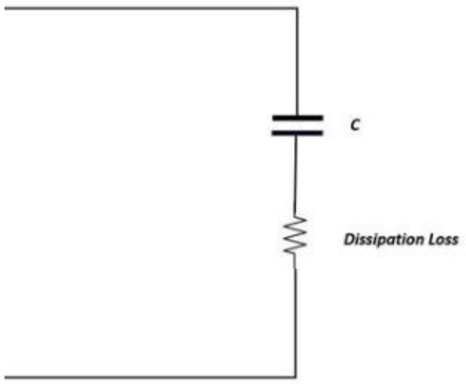


Fig. 7 Piezo speaker impedance

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.

Application Hints

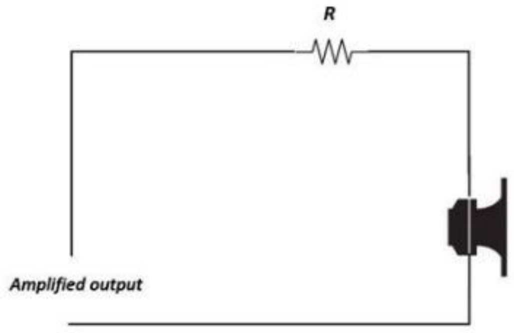
With all the aforementioned virtues of piezo tweeters, there are still some issues in their use with which the design engineer should be familiar.



***C value** is =* *0.12µF for 4kHz Tweeter*
0.30µF for 2kHz Horn
1.20µF for 800Hz Horn Driver

Fig. 8 Piezo tweeter equivalent circuit

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.



Speaker family	***R***
3-6kHz Tweeter	*50Ω 2W*
2kHz Horn	*Not required*
800Hz Horn Driver	*20Ω 10W*

Fig. 9 Protective series resistor

If such an amplifier is used, particularly with an array of tweeters, a small series resistor is suggested (Figure 9). For Piezo Source tweeters with a low-end cutoff of 3 kHz to 6 kHz, a 50Ω, 2W 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 20Ω, 10W 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.

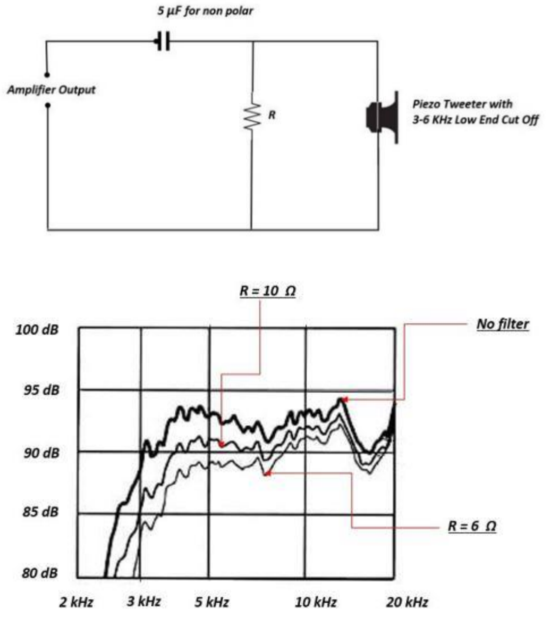
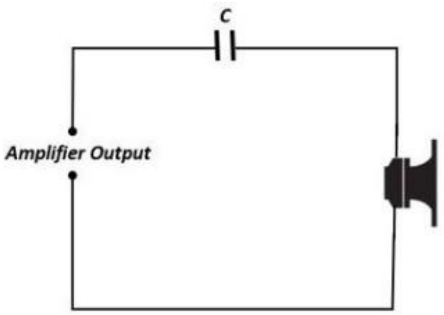


Fig. 10 Singe stage R-C filter for attenuating turn on response

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 8Ω 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 8Ω 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.



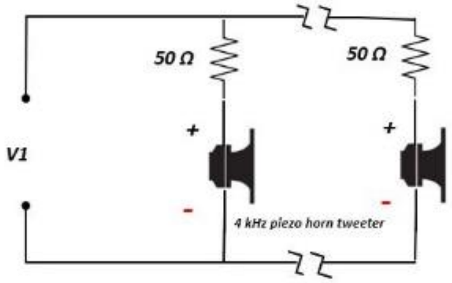
Speaker family	*C*	*Attenuation*
3-6kHz Tweeter	*0.1µF* *0.04µF*	*6dB* *12dB*
2kHz Horn	*0.3µF* *0.12µF*	*6dB* *12dB*

Fig. 11 Series attenuating capacitor

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

Multiple Tweeters

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

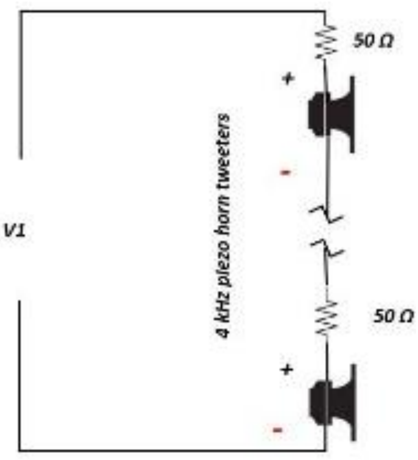


Number of tweeters connected in parallel	*Average sensitivity change (dB)*	*On axis sensitivity change (dB)*
1	0 (ref)	0(ref)
2	+3	+6
3	+5	+10
4	+6	+12
8	+9	+18

Fig. 12 Output level increase for parallel connected piezo tweeters

Each time the number of tweeters connected in parallel is doubled, the average sensitivity for the array increases by 3 to 6dB. The actual increase depends on factors such as off-axis angle, frequency, tweeter model and the configuration of the array. For Piezo Source Super Horns, the on-axis response increases 6dB 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.

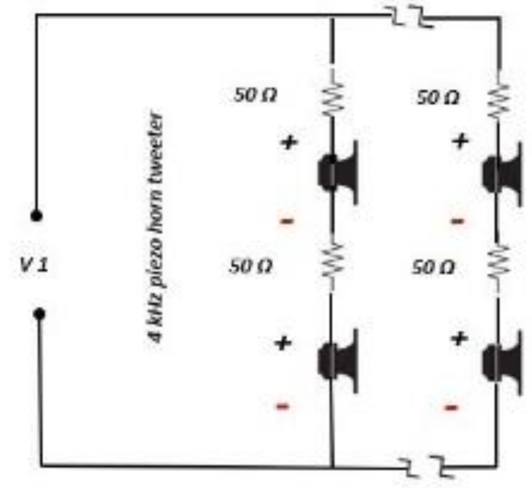
Number of tweeters connected in series	*Average sensitivity change (dB)*	*On axis sensitivity change (dB)*	*On axis SPL at max power rating (dB)*
1	*0 (ref)*	*0(ref)*	*0 (ref)*
2	*-3*	*+6*	*+6*
3	*-5*	*+10*	*+10*
4	*-6*	*+12*	*+12*



Number of tweeters connected in series	*Max array EIA voltage (V1 rms volts)*	*Max array EIA power (watts ref to 8Ω)*
1	*25*	*75*
2	*50*	*300*
3	*75*	*700*
4	*100*	*1250*

Fig. 13 Output level for series connected piezo 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.



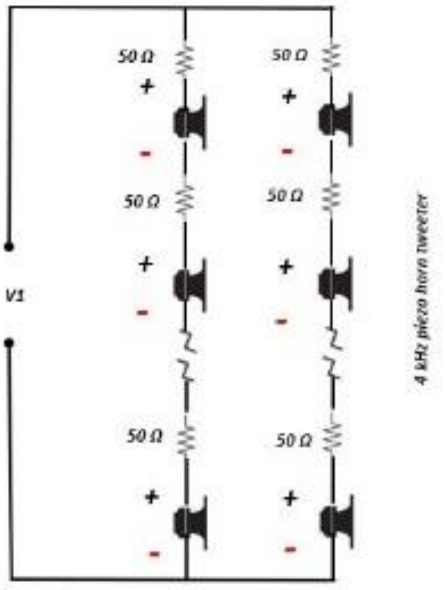
Number of pairs connected	*Average sensitivity change (dB)*	*On axis sensitivity change (dB)*	*On axis SPL at max power rating (dB)*
1	*-3*	*+3*	*+9*
2	*0*	*+6*	*+12*
4	*+3*	*+9*	*+15*
8	*+6*	*+12*	*+18*

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

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 6dB increase for a net on-axis sensitivity change of 0dB. If the voltage applied to the array is now doubled, so that each tweeter sees its maximum rated voltage, the array's on-axis SPL increases 6dB.

Total numbers of tweeter connected	*Average sensitivity change (dB)*	*On axis sensitivity change (dB)*	*On axis SPL at max EIA related power (dB)*
1	*0 (ref)*	*0(ref)*	*0 (ref)*
2	*+3*	*+6*	*+6*
3	*0*	*+6*	*+12*
4	*-3*	*+6*	*+18*



Total numbers of tweeter connected	*Max array EIA voltage (V1 rms volts)*	*Max array EIA power (watts ref to 8Ω)*
1	*25*	*75*
2	*25*	*75*
3	*50*	*300*
4	*100*	*1250*

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

Power Handling

The power rating of Piezo Source 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, Piezo Source 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 Piezo Source 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).

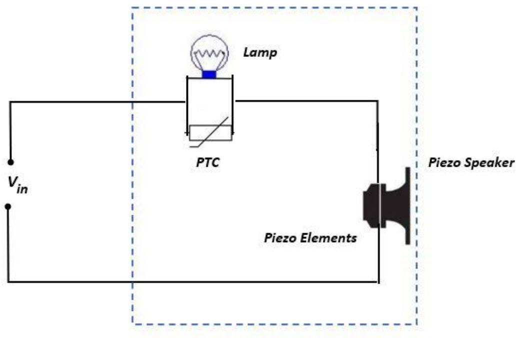


Fig. 16 Powerline internal protection circuit

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 its 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 Piezo Source product line of piezo tweeters has grown dramatically since the Super Horn made its debut 18 years ago. Piezo Source's speaker portfolio now includes mid-range drivers, voice range products, 2 kHz horns, and the Power Line family. Piezo Source 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.

More Applications

SODAR

Doppler effect is the difference in frequency between the wave transmitted or wave that leaves a source and the wave received or wave that reach the receiver due to the relative motion of source and receiver, while sound reflection is the reflection of the sound when it hits the surface of an object [13]. These two, the Doppler effect and sound reflection, are some of the concepts that the SODAR instrument used.

SODAR is an acronym for Sound Detection and Ranging which is an instrument that used sound waves to investigate the lower atmosphere [14]. It is generally used as a wind profiler which measures the wind speed, the wind direction, and the vertical wind speed at various heights above the ground [15]. It is also called acoustic echo sounders (AES), echosounder, and acoustic radar.

SODAR produces sound waves directly above the atmosphere at different angles. As the sound wave travels, the sound wave attenuates by the temperature and humidity in the atmosphere. When the sound wave hit wind turbulence in the atmosphere, the sound wave is reflected. The reflected sound wave, which now has different intensity and frequency, goes back to SODAR.

The received sound wave is then compared to the transmitted sound wave and the following were acquired:

- time delay or the time the sound wave travels
- intensity difference or the difference in amplitude of the wave
- Doppler shift or the difference in wave frequency

Turbulent strength is acquired using the intensity difference, height using the time delay and sound speed, wind speed using the Doppler shift or the frequency difference, and wind direction using the sound wave received in different angles [2].

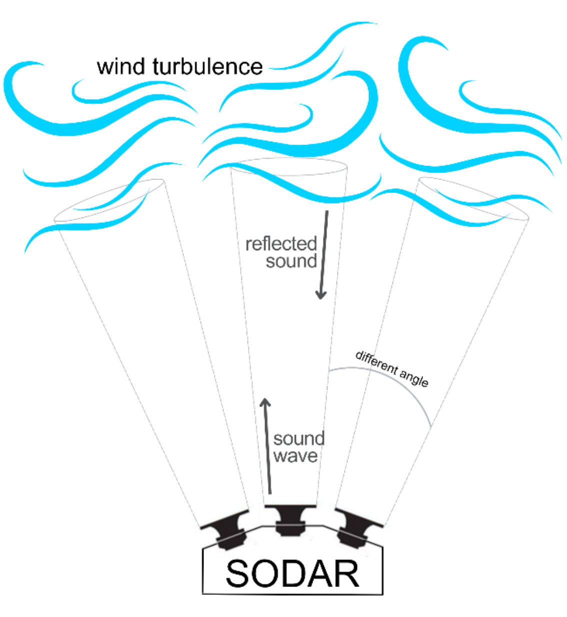


Fig. 17 SODAR working principles

SODAR used remote sensing for air observation. It is a much smaller instrument compared to meteorological towers, so it is easy to install and collect data. Although it is smaller, it shows a very good correlation both in wind speed and wind direction to the meteorological towers [16]. It is now used in many applications such as:

1. Meteorological Monitoring
2. Wind Power Generation
3. Airport Low Altitude Wind Monitoring
4. Wind Resource Assessment and Measurement
5. Meteorological Research

LRAD

When two waves have the same frequency and phase and interacted, they will combine and produce a stronger wave which process is called constructive interference [13]. Since sound is a wave, this process can also be applied to speakers. The produced sound wave due to constructive interference has a higher amplitude and intensity than the former two waves. And when two sounds are out of phase, they will cancel each other producing lesser waves which process is called destructive interference [13]. The produced sound wave due to destructive interference have lower amplitude and intensity. Constructive and destructive interference is the main principles that LRAD used for creating a directional very loud sound.

LRAD or Long-Range Acoustic Device is a device that American Technology Corporation developed as a substitute and discourages in use of lethal force in US military ships [17]. It is also called an acoustic hailing device (AHD) and sound canon.

LRAD uses piezoelectric transducers to produce sound in a speaker. Many piezoelectric speakers are then aligned in an array and connected to an electrical power source. The power source applies electrical current to the transducers which will then each create sound waves. Identical sound waves, having the same phase and frequency, are then produced in the array of transducers. Due to constructive interference, the sound wave produced has a higher amplitude that helps LRAD have powerful sounds. [18]

Unlike other dispersed speakers' sounds, LRAD produces a focused beam of sound. It is a directional model which creates a sound that travels farther than other speakers. To have a directional LRAD, the outer speakers' sound wave must not be in phase with the inner speakers in the array of piezoelectric transducer speakers. When LRAD produces sounds, the sound waves in the outermost will cancel each other out or destructive interference happen. The LRAD sounds produced have less intensity or are less loud in the outermost compared to the innermost sound. [18]

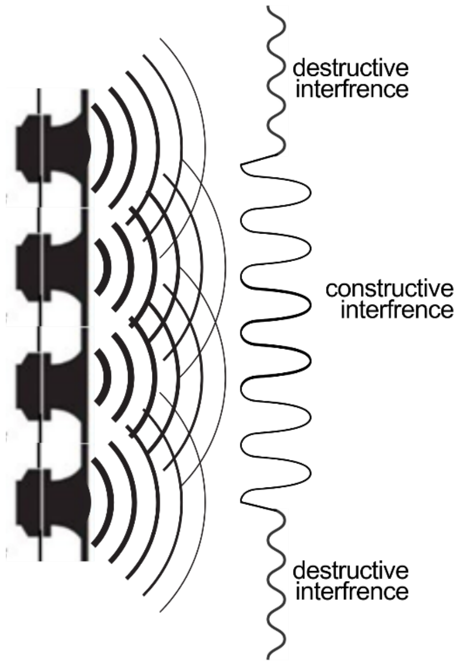


Fig. 18 LRAD Sound Production

The maximum distance an LRAD can cover depends on the sound level, directionality, and frequency of the acoustic source, the sensitivity and directionality of the receiver, and the transmission channel environment.

Aside from a loud painful sound, LRAD can also amplify voices that are loud and clear. Since it can travel to longer distances, LRAD can be used in many applications such as:

1. Maritime Shipping, Safety, and Communication
2. Mass Notification
3. Early Warning Systems
4. Critical Infrastructure Protection
5. Wildlife Protection and Control
6. Crowd Control
7. Long Range Communication

Sound Energy Harvester

Since piezoelectric speakers cannot only convert electrical energy to mechanical energy but also convert mechanical energy to electrical energy. So piezoelectric speakers can be used as a sound energy harvester.

Sound or noise can be found in many places such as roads, airports, factories, etc., so it is one of the energies that is underutilized by people. Though it is a big challenge since sound energy has low power density. A simple sound energy harvesting system has the components of a noise or sound source, a piezoelectric transducer, an electric circuit, and a charge storage [19].

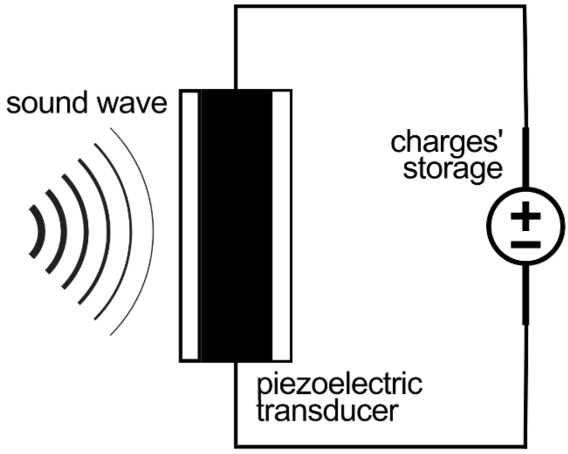


Fig. 19 Sound Energy Conversion Diagram

The output voltage produced by the piezoelectric transducer can be increased by using a transformer that produced a 0.5V to 1.0V electrical voltage [20]. Another way of increasing the output voltage is by connecting it to Villard and Dickson voltage multipliers increased produced an approximately 10V output voltage using the 96dB sound intensity level [21. Up until today, there is still continuous research by scientists and engineers on creating an efficient sound energy harvester.

Pest Repellant

Pest Repellant is an electrical device that uses sound to keep out animals such as rats, birds, and many more animals from a selected zone. Some examples of these devices are rat repellants, bird scarers, and dog barking preventers.

A rat repellant is an electrical device that produces frequency greater than 15kHz sound waves which are inaudible to people, but unpleasant to rats [22]. Dog barking preventers also used higher frequency inaudible to humans [23].

The bird scarer on the other hand used a lesser frequency greater than 1kHz sound waves to scare the birds [24]. Despite using different frequencies, all of these pest-repellant devices used the same mechanism and circuit

These pest repellants are used in many places where animals can be considered a pest such as:

1. Crop Farming and Fish Pond Farming
2. Airport Runways
3. Parks, Malls, Parking Lots, etc.

The piezoelectric speaker is a better device as a pest repellant because it is a cost-effective solution, safe and humane, non-poisonous, simple to install, can be used in a range of locations, and can withstand harsh environments.

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KSN 1001A Super Horn Datasheet

Applications

Specific Applications	- SODAR (Wind Profiling) - LRAD Long Range Acoustic Device - Automotive, Aircraft, Trains, Ships - Radios - Medical Equipment - High Fidelity Sound Reproduction - Bioacoustics - Alarms/Alerts - Transducer - Pest Repellent (Rodents, Birds, etc.)

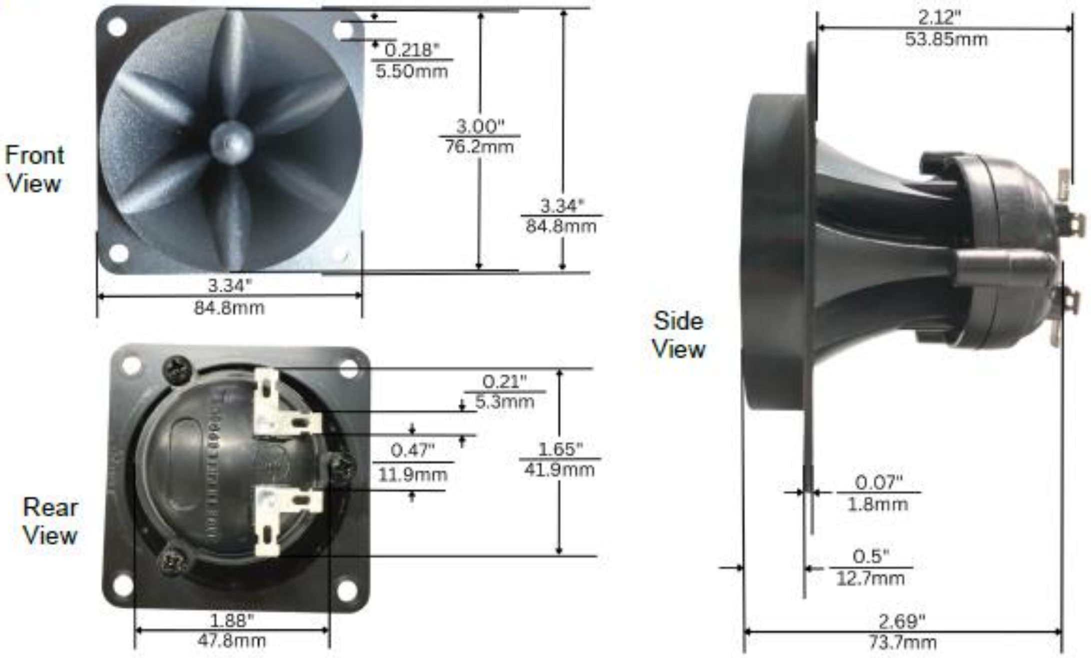
Features

1. Low power consumption
2. High sensitivity
3. Withstand harsh environment

Packaging Information

Specifications	Standard Packing Quantity	Gross Weight
14"x15"x19"	100	8.18 kgs

Appearances and Dimensions



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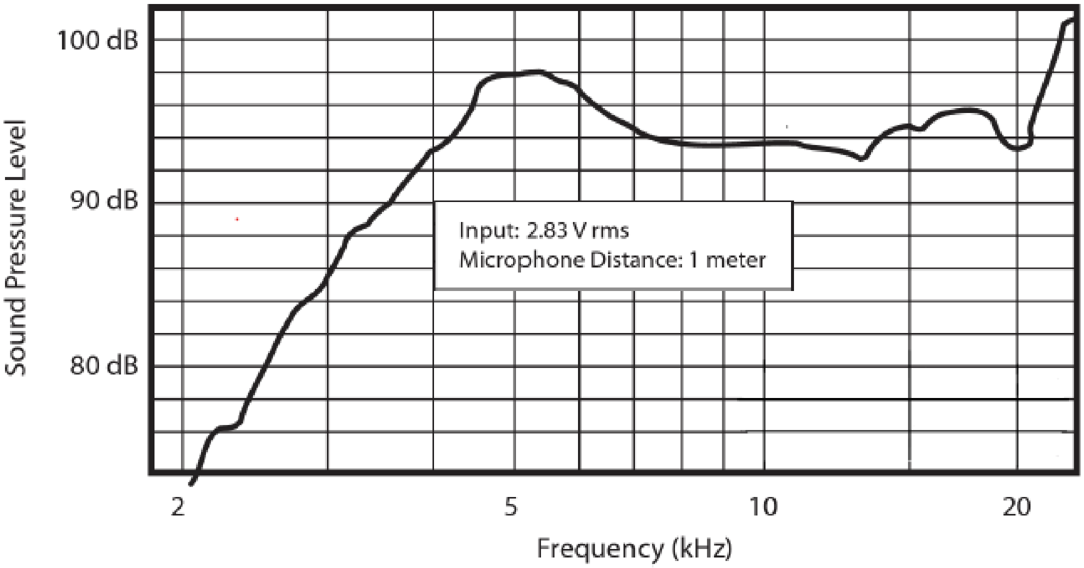
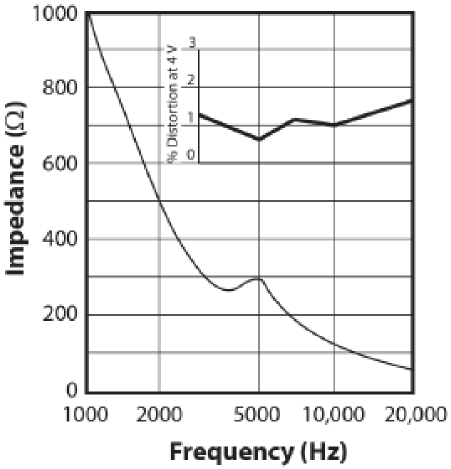
Frequency Response



Impedance Plot



Specifications

Frequency Response	4kHz to 20kHz
Average Sensitivity	94 dB at 1m/1W
Maximum Power Handling Capacity	75 W (EIA RS426) 8Ω system reference
Maximum Voltage	15 Vrms continuous 35 Vrms intermittent
Maximum Temperature	80°C
Typical Impedance	Appears as a 0.13μF capacitor
Weight	75g

Warning: A 30-ohm series resistor is recommended to assure stability of extended range amplifiers and preclude hazard of burnout.

Warning: Do not operate at continuous high voltage. At frequencies below 20 kHz, daily sound pressure exposures in excess of one hour at 105 dB may lead to hearing impairment.