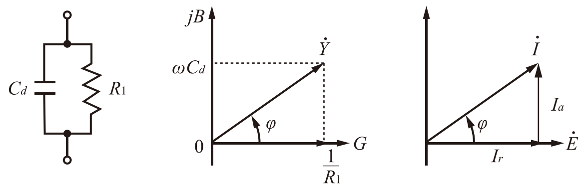
Guide for Using Piezoelectric Elements

■Correlation between Electrical and Mechanical Systems

Electrical Domain	Voltage	Current	Charge	Electrical Resistance	Inductance	Capacitance	Impedance	Admittance
	V	I	Q	R	L	C	Z	Y
Mechanical Domain	Force	Velocity	Displacement	Mechanical Resistance	Mass	Compliance	Mechanical Impedance	Mechanical Admittance
	f	v	u	r	m	s_n	Z_m	Y_m

■Impedance matching

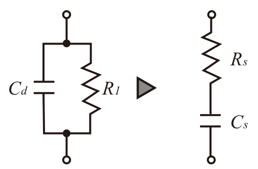
The ceramic vibrator has capacitive impedance at the resonance point. For this reason, an efficient drive cannot be performed even if it inputs electric power from an oscillator. The following is guidance for supplying electric power effectively. Please check the absolute value of the capacitive reactance of a vibrator. Please prepare inductive reactance (chalk coil) equal to this absolute value. Please connect this to a vibrator and parallel (or series), and cancel reactance.



Vector chart at the time of the vibrator resonance

Equivalent circuit of the vicinity of the resonance point of the vibrator is constructed of the L_1, C_1, R_1 and C_d. For C_1 and L_1 is canceled, it will be parallel circuit of C_d and R_1. And impedance Z of the vibrator will be $1/\omega C_d$. The equal ωL_p to the absolute value of Z are connected in parallel. Since the Z is canceled, the impedance of the vibrator will be only R_1. And, become $R_g = R_1$ if the output resistance of the oscillator is the R_g. In this way you can most efficient drive. The following is easy way. Adjust the output transformer of N:1 winding ratio. To adjust to the winding ratio of $R_g = N^2 R_1$.

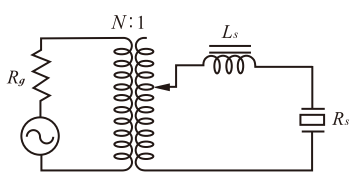
R_1 is correspondence with the mechanical load of the vibrator. It will also change the value of R_1 by the largeness of the load. For example, in the water load, it will change significantly over the depth and cavitation existence. It must be measured on actual use conditions. In addition, parallel equivalent circuit can also be changed to a series circuit of the $R_s - C_s$. Also in this case, a choke coil L_s with an absolute value equal to $1/\omega C_s$ is connects in series. And can cancel the C_s by doing this.



$$R_s = \frac{R_1}{1 + (\omega C_d R_1)^2}$$

$$C_s = \frac{1 + (\omega C_d R_1)^2}{(\omega C_d R_1)^2} \cdot C_d$$

Series equivalent transformation of the vibrator



Impedance matching circuit example of the vibrator

■Calculation of output with respect to the force F

Impressing a force F, there is application to generate the charge Q or voltage V. This is the applications of the machine-electrical transduction. Piezoceramics will generate a charge Q. The total charge Q is corresponding to the applied force F through the factor of proportionality of size, piezoelectric constant d_{33}, capacitance C_d and others.

$$Q = C_d \cdot V = F \cdot d_{33}$$

This output voltage V is the relationship formula of following due to the piezoelectric constants g_{33} and the piezoceramics element thickness t and crosssection.

$$V = F \cdot d_{33}/C_d = F \cdot g_{33} \cdot t/A$$

Charge Q generated in the piezoelectric element corresponds to the magnitude of the force F. If the force F is constant, the charge Q is also constant. Insulation resistance value of the piezo elements, which is also regarded as a kind of condenser (capacitor) is finite. For that reason, the charge Q generated will get discharged in accordance with the time constant $C_d R$ in the following formula.

$$q = Q e^{-t/C_d R}$$ q: Actual apparent charge

For example, in the case of applying the piezo elements to the pressure sensor, it does not have a static sensitivity.
Force F, can be expansion as the AC, by the relationship between mass m, acceleration α, displacement u, the angular frequency ω. Refer to the following formula.

$$F = m \cdot \alpha = m \cdot u \cdot \omega^2 = m \cdot u \cdot (2\pi f)^2$$

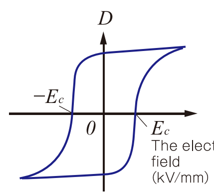
■Calculation of displacement with respect to the input voltage V

Impressing a voltage V, there is application to produce the strain. It will be applied to obtain a mechanical output from the electrical input. And that is driven by AC as of ultrasonic equipments, there is a thing to be driven by an AC of the DC or low frequency. The displacement u of the no-load, and the generative force F is calculated by the following formula. If want to drive in the load and AC, consider those conditions.

$u = V \cdot d_{33}$ V: Input voltage, d_{33}: Piezoelectric constant
$F = u/s_n$ s_n, s_{33}^E: Compliance
$s_n = s_{33}^E \cdot t/A$ t, A: Thickness, Area

■Anti-electric power (Anti-electric field & Anti-voltage)

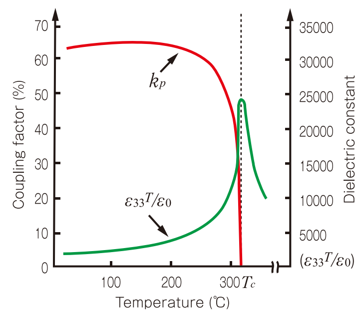
Piezoelectric elements are polarized by applying a high DC voltage, which aligns the spontaneous polarization and creates residual polarization, thereby giving them piezoelectric properties. When a voltage is applied in the opposite direction, the electric field that the residual dielectric polarization will be a zero is called the anti-electric power E_c.
The value of the anti-electric power E_c will vary depending on the material of the piezo elements. If want to apply the high voltage of an inverse to the direction of polarization electric field be careful. The depolarization characteristics of the residual polarization is, becomes a functions of voltage, time, temperature and others. Accordingly it will vary depending on the conditions at that time. With respect to the between electrode thickness of the piezo elements, the electric field of several tens to several hundred volts will be the limit.



Anti-electric power of the piezo ceramics

■Maximum use temperature

The characteristics of polarized piezoelectric elements remain stable at lower temperatures. However, at higher temperatures, a phase transition point (Curie point Tc) exists, which limits their operating temperature range. In the Curie point T_c, the dielectric constant is increased to infinity. In the result, the crystal becomes unstable, the crystal structure will transition phase. As a result, the spontaneous polarization and the residual polarization are lost. And the piezoelectric properties are lost.
When cooled down below the Curie point, the spontaneous polarization is restored. However, since the residual polarization does not recover, the piezoelectric properties are lost. Loss of the residual polarization depends on the temperature and time or material. The problem-free operating temperature is approximately one-third to one-half of the Curie point.



High-temperature characteristics of piezo ceramics (PZT)

■Physical constants at room temperature

Density (ρ)	7.3~7.7×10^3 [kg/m^2]
Line expansion rate (α)	5~10×10^{-6} [1/℃]
Specific heat (C)	500~700 [J/kg・℃]
Coefficient of thermal conductivity (k)	1~1.5 [W/m・℃]
Electric resistance rate	10^{10}~10^{11} [Ω・m]
Compression strength	5~7×10^8 [N/m^2]
Pull strength	0.6~1×10^8 [N/m^2]
Anti-bending strength	0.6~1×10^8 [N/m^2]
Vickers hardness (H V)	350~450
Sonic speed of longitudinal wave (v)	2800~3600 [m/s]

Physical constants at room temperature of the PZT [Pb (Zr・Ti) O_3]

Implementation Note

When considering the implementation of piezo elements, the handling of the electrodes is important. Many electrodes are silver electrodes that undergo high-temperature firing. Nickel electrodes are used for chemical plating. The electrode may cause surface alteration and intensity degradation. Caution is needed when using soldering, adhesive bonding, or chemical conditioning methods.

■Soldering method for the electrodes

For example, the solder uses Alumit LFM48. The maximum temperature of the soldering tip is 270℃. The solder point size should be minimized. It is recommended to work in less than three seconds.

■Adhesive bonding method

Apply an appropriate amount of an epoxy-based adhesive to the degreased adhesive surface. Crimp the adhesive surface and cure it at a temperature of 80℃. Piezoceramics are charged by heating and cooling. It is recommended that large piezoceramics be short-circuited between the electrodes.

■Chemical and environmental resistance to the electrode

Silver and nickel combine with acids, sulfides, and halides.
Therefore, caution is needed regarding the chemical condition.

Conditions	Silver electrodes	Nickel electrodes
In airs	Not oxidized even when heated in oxygen. Within the ozone, it becomes black silver peroxide Ag_2O_2.	Less prone to oxidation in air and moisture.
Acid solutions	Dissolved in sulfuric acid and hot concentrated sulfuric acid, it will be $AgNO_3$, Ag_2SO_4.	Dissolved in sulfuric acid and nitric acid, it will be $NiSO_4$, $Ni(NO_3)_2 \cdot 6H_2O$.
Alkali solutions	Silver is insoluble. Dissolving the glassy contained in the electrode, silver film peeling will arisen.	There is no impact.
Sulfides	It turns black (Ag_2S) when exposed to sulfur or hydrogen sulfide.	Combine with sulfide, it will be NiS.
Halides	Combine with halide, it will be AgCl, and AgBr or AgI, etc.	Combine with halide, it will be $NiCl_2$, etc.
Others	Applying a DC electric field for a long period under high humidity may cause silver migration (short-circuiting due to silver crystal growth). Moisture-proof protection is recommended.	For use in high humidity, moisture-proofing treatment recommended.
Storages	To avoid the heat and humidity, the sealing state is desired. Don't packing with rubber bands or urethane foams.	To avoid the heat and humidity, the sealing state is desired.