Piezoelectric Theory

Piezoelectric effect

The piezoelectric effect was discovered by Pierre and Jacques Curie in 1880. It remained a mere curiosity until the 1940's. The property of certain crystals to exhibit electrical charges under mechanical loading was of no practical use until very high input impedance amplifiers enabled engineers to amplify their signals. In the 1950's electrometer tubes of sufficient quality became available and the piezoelectric effect was commercialized.

W.P. Kistler patented the charge amplifier principal in 1950 and gained practical significance in the 1960's. The introduction of highly insulating materials such as Teflon and Kapton greatly improved performance and propelled the use of piezoelectric sensors into virtually all areas of modern technology and industry.

Piezoelectric measuring systems are active electrical systems. That is, the crystals produce an electrical output only when they experience a change in load. For this reason, they cannot perform true static measurements. However, it is a misconception the piezoelectric instruments are suitable for only dynamic measurements. Quartz transducers, paired with adequate signal conditioners, offer excellent quasistatic measuring capability. There are countless examples of applications where quartz based sensors accurately and reliably measure quasistatic phenomena for minutes and even hours.

Applications of piezoelectric instruments

Piezoelectric measuring devices are widely used today in the laboratory, on the production floor and as original equipment. They are used in almost every conceivable application requiring accurate measurement and recording of dynamic changes in mechanical variables such as pressure, force and acceleration. The list of applications continues to grow and now includes:

- Aerospace: Modal testing, wind tunnel and shock tube instrumentation, landing gear hydraulics, rocketry, structures, ejection systems and cutting force research
- Ballistics: Combustion, explosion, detonation and sound pressure distribution
- Biomechanics: Multi-component force measurement for orthopedic gait and posturography, sports, ergonomics, neurology, cardiology and rehabilitation
- Engine Testing: Combustion, gas exchange and injection, indicator diagrams and dynamic stressing
- Engineering: Materials evaluation, control systems, reactors, building structures, ship structures, auto chassis structural testing, shock and vibration isolation and dynamic response testing
- Industrial/Factory: Machine systems, metal cutting, press and crimp force, automation of force-based assembly operations and machine health monitoring
- OEMs: Transportation systems, plastic molding, rockets, machine tools, compressors, engines, flexible structures, oil/gas drilling and shock/vibration testers.

Piezoelectric sensors (Quartz based)

The vast majority of Kistler sensors utilize quartz as the sensing element. As discussed in other sections of this catalog, Kistler also manufactures sensors which utilize piezo-ceramic elements and micro machined silicon structures. However, the discussion in this section will be limited to quartz applications. Quartz piezoelectric sensors consist essentially of thin slabs or plates cut in a precise orientation to the crystal axes depending on the application. Most Kistler sensors incorporate a quartz element, which is sensitive to either compressive or shear loads. The shear cut is used for patented multi-component force and acceleration measuring sensors. Other specialized cuts include the transverse cut for some pressure sensors and the patented polystable cut for high temperature pressure sensors.
See figure 1 and 2.

Although the discussion which follows focuses on accelerometer applications, the response function for force and pressure sensors has essentially the same form. In fact, many force applications are closely related to acceleration. On the other hand, pressure sensors are designed to minimize or eliminate (by direct compensation of the charge output) the vibration effect. Call Kistler directly for more information on this subject or refer to the inside back cover which lists available technical articles.

The finely lapped quartz elements are assembled either singly or in stacks and usually preloaded with a spring sleeve. The quartz package generates a charge signal (measured in picoCoulombs) which is directly proportional to the sustained force. Each sensor type uses a quartz configuration which is optimized and ultimately calibrated for its particular application (force, pressure, acceleration or strain). Refer to the appropriate section for important design aspects depending on application.

Quartz sensors exhibit remarkable properties, which justify their large scale use in research, development, production and testing. They are extremely stable, rugged and compact. Of the large number of piezoelectric materials available today, quartz is employed preferentially in sensor designs because of the following excellent properties:

- High material stress limit, approximately 20,000 psi
- Temperature resistance up to 930°F
- Very high rigidity, high linearity and negligible hysteresis
- Almost constant sensitivity over a wide temperature range
- Ultra high insulation resistance (10^{14} ohms) allowing low frequency measurements (<1 Hz)

High and low impedance

Kistler supplies two types of piezoelectric sensors: high and low impedance. High impedance units have a charge output which requires a charge amplifier or external impedance converter for charge-to-voltage conversion. Low impedance types use the same piezoelectric sensing element as high impedance units and also incorporate a miniaturized built-in charge-to-voltage converter. Low impedance types require an external power supply coupler to energize the electronics and decouple the subsequent DC bias voltage from the output signal.

Dynamic behavior of sensors

Piezoelectric sensors for measuring pressure, force and acceleration may be regarded as under-damped, spring mass systems with a signal degree of freedom. They are modeled by the classical second order differential equation whose solution is:

$$\frac{a_o}{a_b} \cong \frac{1}{\sqrt{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2+\left(\frac{1}{Q^2}\right)\left(\frac{f}{f_n}\right)^2}}$$

Where:

f_n = undamped natural (resonant) frequency (Hz)

f = frequency at any given point of the curve (Hz)

a_o = output acceleration

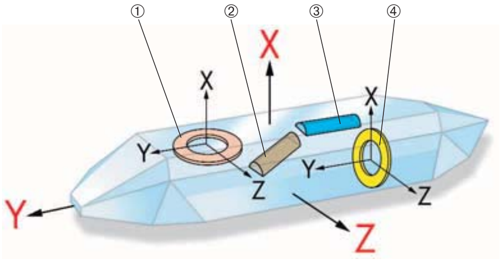
a_b = mounting base or reference acceleration ($f/f_n = 1$)

Q = factor of amplitude increase at resonance

Quartz sensors have a Q of approximately 10 to 40 and therefore the phase angle can be written as:

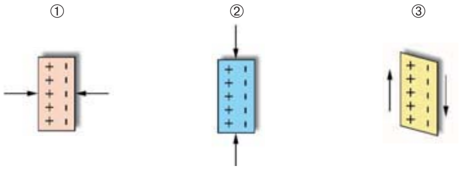
$$\text{phase lag (deg)} \cong \frac{60}{Q}\left(\frac{f}{f_n}\right) \text{ for } \frac{f}{f_n} \le \frac{2}{5}$$

A typical frequency response curve is shown in figure 3. As shown, about 5% amplitude rise can be expected at approximately 1/5 of the resonant frequency (f_n). Low-pass (LP) filtering can be used to attenuate the effects of this. Many Kistler signal conditioners (charge amplifiers and couplers) have plug-in filters for this purpose.



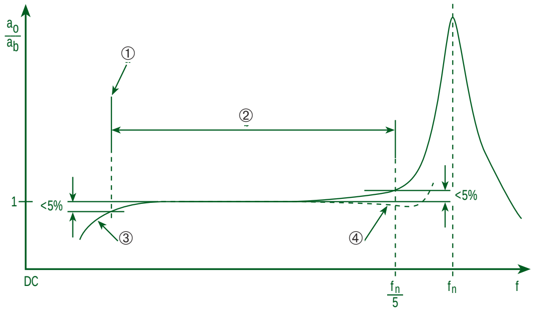
① = compression cut
② = polystable cut
③ = transverse cut
④ = shear cut

Figure 1
Quartz bar



① = longitudinal effect
② = transverse effect
③ = shear effect

Figure 2
Piezoelectric effect



① = low frequency limit determined by RC roll-off characterstics
② = useable range
③ = HP filter
④ = with LP filter

Figure 3
Typical frequency response curve

Charge amplifiers

Basically the charge amplifier consists of a high-gain inverting voltage amplifier with a MOSFET or J-FET at its input to achieve high insulation resistance. A simplified model of the charge amplifier is shown in figure 4.

The effects of R_t and R_j will be discussed below. Neglecting their effects, the resulting output voltage becomes:

$$V_o = \frac{-q}{C_r} \times \frac{1}{1 + \frac{1}{AC_r}\left(C_t + C_r + C_c\right)}$$

For sufficiently high open loop gain, the cable and sensor capacitance can be neglected and the output voltage depends only on the input charge and the range capacitance.

$$V_o = \frac{-q}{C_r}$$

In summary, the amplifier acts as a charge integrator which compensates the sensor's electrical charge with a charge of equal magnitude and opposite polarity and ultimately produces a voltage across the range capacitor. In effect, the purpose of the charge amplifier is to convert the high impedance charge input (q) into a useable output voltage (V_o).

Time constant and drift

Two of the more important considerations in the practical use of charge amplifiers are time constant and drift. The time constant is defined as the discharge time of an AC coupled circuit. In a period of time equivalent to one time constant, a step input will decay to 37% of its original value.

Time Constant (TC) of a charge amplifier is determined by the product of the range capacitor (C_r) and the time constant resistor (R_t):

$$TC = R_t C_r$$

Drift is defined as an undesirable change in output signal over time, which is not a function of the measured variable. Drift in a charge amplifier can be caused by low insulation resistance at the input (R_j) or by leakage current of the input MOSFET or J-FET.

Drift and time constant simultaneously affect a charge amplifiers output. One or the other will be dominant. Either the charge amplifier output will drift towards saturation (power supply) at the drift rate or it will decay towards zero at the time constant rate.

Many Kistler charge amplifiers have selectable time constants which are altered by changing the time constant resistor (R_t). Several of these charge amplifiers have a "Short", "Medium" or "Long" time constant selection switch. In the "Long" position, drift dominates any time constant effect. As long as the input insulation resistance (R_j) is maintained at greater than 10^{13} ohms, the charge amplifier (with MOSFET input) will drift at an approximate rate of 0.03 pC/s. Charge amplifiers with J-FET inputs are available for industrial applications but have an increased drift rate of about 0.3 pC/s.

In the "Short" and "Medium" positions, the time constant effect dominates normal leakage drift. The actual value can be determined by referring to the appropriate operation/instruction manual which is supplied with the unit. Kistler charge amplifiers without "Short", "Medium" or "Long" time constant selection, operate in the "Long" mode and drift at the rates listed above. Some of these units can be internally modified for shorter time constants to eliminate the effects of drift.

Frequency and time domain considerations

When considering the effects of time constant, the user must think in terms of either frequency or time domain. The longer the time constant, the better the low-end frequency response and the longer the useable measuring time. When measuring vibration, time constant has the same effect as a single-pole, high-pass (HP) filter whose amplitude and phase are:

$$\frac{V_o}{V_{in}} = \frac{2\pi f\,(TC)}{\sqrt{1+\left[2\pi f\,(TC)\right]^2}}$$

$$\text{phase lead (deg)} = \arctan \frac{1}{2\pi f\,(TC)} \cong 80\sqrt{\frac{V_{in} - V_o}{V_{in}}}$$

For example, the output voltage has declined approximately 5% when f x (TC) equals 0.5 and the phase lead is 18 degrees.

When measuring events with wide (or multiple) pulse widths. The time constant should be at least 100 times longer than the total event duration. Otherwise, the DC component of the output signal will decay towards zero before the event is completed.

Selection matrix

Other design features incorporated into Kistler charge amplifiers include range normalization for whole number output, low-pass filters for attenuating sensor resonant effects, electrical isolation for minimizing ground loops and digital/computer control of setup parameters.

Low impedance piezoelectric sensors

Piezoelectric sensors with miniature, built-in charge-to-voltage converters are identified as low impedance units throughout this catalog. These units utilize the same types of piezoelectric sensing element(s) as their high impedance counterparts. Piezotron, Picotron, PiezoBeam, Ceramic Shear and K-Shear are all forms of Kistler low impedance sensors.

In 1966, Kistler developed the first commercially available piezoelectric sensor with internal circuitry. This internal circuit is a patented design called Piezotron. This circuitry employs a miniature MOSFET input stage followed by a bipolar transistor stage and operates as a source follower (unity gain). A monolithic integrated circuit is utilized which incorporates these circuit elements. This circuit has very high input impedance (10^{14} N) and low output impedance (100 N) which allows the charge generated by the quartz element to be converted into a useable voltage. The Piezotron design also has the great virtue of requiring only a single lead for power-in and signal-out. Power to the circuit is provided by a Kistler coupler (Power Supply), which supplies a source current (2–18 mA) and energizing voltage (20–30 VDC). Certain (extreme) combinations of other manufacture's supply current and energizing voltage (i.e. 20 mA and 18 VDC, respectively), together with actual bias level, may restrict operating temperature range and voltage output swing. Call Kistler for details. Connection is as shown in figure 5. A Kistler coupler and cable is all that is needed to operate a Kistler low impedance sensor.

The steady state output voltage is essentially the input voltage at the MOSFET Gate plus any offset bias adjustment. The voltage sensitivity of a Piezotron unit can be approximated by:

$$V_o \cong \frac{q}{C_q + C_r + C_G}$$

The range capacitance (C_r) and time constant resistor (R_t) are designed to provide a predetermined sensitivity (mV/g) and upper and lower useable frequency. The exact sensitivity is measured during calibration and its value is recorded on each unit's calibration certificate.

Since its invention, the Piezotron design has been adapted by manufactures worldwide and has become a widely used standard for design of sensors which measure acceleration, force and pressure. The concept has become known by many names besides Piezotron such as low impedance or voltage mode. Also, a number of "brand names" have emerged by other manufactures.

Picotron is a miniature accelerometer whose circuitry is very similar to the Piezotron. PiezoBeam incorporates a bimorph ceramic element and a miniature hybrid charge amplifier for the charge-to-voltage conversion. K-Shear is the newest member of the Kistler low impedance family and utilizes a shear quartz element together with the Piezotron circuitry.

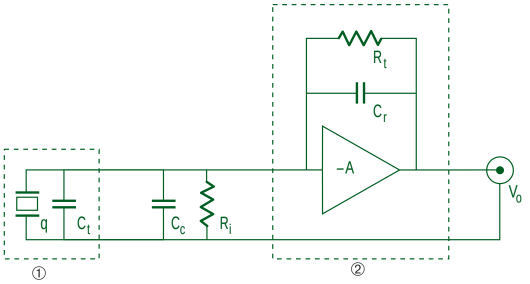
Time constant

The time constant of a Piezotron or Picotron sensor is:

$$TC = R_t\,(C_q + C_r + C_G)$$

A PiezoBeam's time constant is the product of its hybrid charge amplifier's range capacitor and time constant resistor.

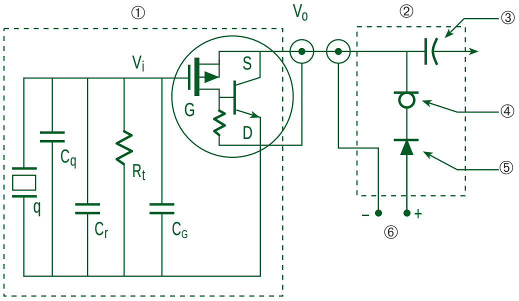
Time constant effects in low impedance sensors and in charge amplifiers are the same. That is, both act as a single pole, high-pass filter as discussed previously.



① = piezoelectric accelerometer
② = charge amplifier
V_o = output voltage
A = open loop Gain
C_t = sensor capacitance
C_c = cable capacitance

C_r = range (or feedback) capacitor
R_t = time constant resistor (or insulation of range capacitor)
R_i = insulation resistance of input circuit (cable and sensor)
q = charge generated by the sensor

Figure 4
Simplified charge amplifier model



① = accelerometer
② = coupler
③ = decoupling capacitor
④ = constant current diode
⑤ = reverse polarity protection diode
⑥ = DC source
q = charge generated by piezoelectric element

V_i = input signal at gate
V_o = output voltage (usually bias decoupled)
C_q = sensor capacitance
C_r = range capacitance
C_G = MOSFET GATE capacitance
R_t = time constant resistor

Figure 5
Piezotron
Circuit & coupler

Low impedance power supply (coupler)

All of the low impedance types mentioned earlier require similar excitation for their built-in electronics. A single two-wire coaxial cable and a Kistler power supply coupler is all that is needed. Both the power into and the signal out from the sensor are transmitted over this two-wire cable. The coupler provides the constant current excitation required for linear operation over a wide voltage range and also decouples the bias voltage from the output.

Time constant

Bias decoupling methods can be categorized as AC or DC. DC methods of bias decoupling will not effect a low impedance sensor's time constant and therefore permit optimum low frequency response. An offset voltage adjust is used to "zero" the bias. AC decoupling methods, however, can shorten the low impedance sensor's time constant and degrade low frequency response. In low impedance systems, with AC bias decoupling, the system time constant can be approximated by taking the product of the sensor and coupler time constants and dividing by their sum. The resulting frequency response can be computed as before.

Selection matrix

Many other performance features are incorporated into Kistler's line of power supply couplers. Included are versions with multi-channel inputs, 100X gain, plug-in filters and computer controlled set-up parameters.

Dual mode charge amplifiers

Another method for powering low impedance sensors is to use a Dual Mode charge amplifier (high/low impedance). Dual mode units can be used as standard charge amplifiers with high impedance sensors or as couplers (with adjustable gain) for low impedance units.

High and low impedance system comparison

Similarities

Both systems utilize the same type of piezoelectric sensing element(s) and therefore are AC coupled systems with limited low frequency response or quasistatic measuring capability. Their respective time constants determine the useable frequency range.

High impedance systems

Usually high impedance systems are more versatile than low impedance. Time constant, gain, normalization and reset are all controlled via an external charge amplifier. In addition, the time constants are usually longer with high impedance systems allowing easy short-term static calibration. Because they contain no built-in electronics, they have a wider operating temperature range.

Low impedance systems

Generally, low impedance systems are tailored to a particular application. Since the low impedance sensor has an internally fixed range and time constant, it may limit use to their intended application. High impedance systems, with control of range and time constant via an external charge amplifier, have no such restriction.

However, for applications with well-defined measuring frequency and temperature ranges, low impedance (Piezotron) systems offer a potentially lower cost (i.e. charge amplifier vs. coupler cost) alternative to high impedance systems. In addition, low impedance sensors can be used with general purpose cables in environments where high humidity/contamination could be detrimental to the high insulation resistance required for high impedance sensors. Also, longer cable lengths, between sensor and signal conditioner and compatibility with a wide range of signal display devices are further advantages of low impedance sensors.

External impedance converters

An alternative method for processing charge from high impedance sensors is to use an external impedance converter. This method is often used to exploit the high temperature range of high impedance sensors while implementing the convenience and cost effectiveness of the coupler.

External impedance converters incorporate the same circuitry as the Piezotron. The only difference is that the sensor cable capacitance must be added to the sensor capacitance (C_q).

Sensor quality/calibration

Over the years, the Kistler name has become synonymous with QUALITY. We at Kistler are dedicated to continuous improvement in all areas; Design, Manufacturing, Quality Control, Quality Assurance and Calibration.

All Kistler products are manufactured in conformance with the requirements of ISO 9001 and MIL-I-45208A. Kistler's calibration system complies with the requirements of MIL-STD-45662A and ANSI/NCSL Z540. Calibrations performed at Kistler are traceable to the National Institute of Standards and Technology (NIST), or the Swiss Federal Office of Metrology. Kistler takes full advantage of the latest technology, performing computer controlled testing, calibration and data collection. Kistler products are used as primary standards for many of the world's leading test and national calibration laboratory facilities, including NIST.

Kistler calibration techniques

Force sensors

The calibration of force sensors is very similar to pressure sensors. The unit under test is calibrated against a standard force ring whose calibration is traceable to NIST. A hydraulic press is used to generate forces for this calibration.

Accelerometers

Kistler acceleration standards are periodically calibrated by an independent third party providing NIST traceability. These primary standards are used to calibrate a set of working standards at Kistler. The working standards are configured to accept direct mounting of the unit under test. "Back to Back" calibration technique minimizes errors. Calibration is performed on a sinusoidal motion shaker.