APPLICATION NOTE: AN-102

Selecting Piezoresistive vs. Piezoelectric Pressure Transducers

(General Measurement)

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Introduction

This application note provides a technical comparison of pressure transducers utilizing piezoresistive and piezoelectric sensing elements in an effort to aid engineers in selecting the most appropriate transducer for an application. Engineers and scientists making pressure measurements may not be aware of the enormous strides made in the field of piezoresistive-based sensors over the previous few decades. Over the same time period, piezoelectric technology has basically remained unchanged. With advancements in the miniaturization, vibration insensitivity, and reduced thermal shift of piezoresistive-based sensors, their usage is increasing in applications where high accuracy, static and/or dynamic pressure measurements are required. It is the purpose of this application note to describe and compare the properties of both technologies and showcase why Silicon on Insulator (SOI) Piezoresistive sensors have become the preferred choice for most needs throughout the industry.

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1. Technology Comparison (Piezoresistive vs. Piezoelectric)

Piezoresistive based transducers rely on the piezoresistive effect which occurs when the electrical resistance of a material changes in response to applied mechanical strain. In metals, this effect is realized when the change in geometry with applied mechanical strain results in a small increase or decrease in the resistance of the metal. The piezoresistive effect in silicon is due primarily to changes at the atomic level and is approximately two orders of magnitude larger than in metals[1]. As stress is applied, the average effective mass of the carriers in the silicon either increases or decreases (depending on the direction of the stress, the crystallographic orientation, and the direction of current flow). This change alters the silicon's carrier mobility and hence its resistivity. When piezoresistors are placed in a Wheatstone bridge configuration and attached to a pressure-sensitive diaphragm, a change in resistance is converted to a voltage output which is proportional to the applied pressure.

Piezoelectric-based transducers rely on the piezoelectric effect, which occurs when a crystal re-orients under stress forming an internal polarization. This polarization results in the generation of charge on the crystal face that is proportional to the applied stress[2]. Quartz, tourmaline, and several other naturally occurring crystals exhibit a piezoelectric effect. An electric charge proportional to the applied force is generated when a piezoelectric material is stressed by being coupled to an appropriate force-summing device. Specially formulated ceramics can be artificially polarized to be piezoelectric with sensitivities 100 or more times higher than found in natural crystals[3]. Unlike strain gage sensors, piezoelectric sensors require no external excitation. These sensors exhibit high output impedance and low signal levels; therefore, piezoelectric devices require the use of special equipment such as low-noise coaxial cable and charge amplifiers in the measurement chain.

All piezoelectric sensors are self-generating and develop electrical potential (charge) in proportion to applied stress. Some designs of piezoelectric transducers include an integral preamplifier within the body of the transducer and are known as voltage mode piezoelectric transducers. Sensors designed this way are referred to as IEPE (Integrated Electronic PiezoElectric transducers). The output is internally amplified and the impedance is greatly lowered resulting in simplified signal conditioning. All piezoelectric pressure transducers have an inherent low-frequency rolloff that is dependent on the external signal conditioning's low-frequency time constant. Consequently, they are not usable with DC or steady-state conditions.

Piezoresistive sensors have been and continue to be fabricated from silicon. The older generation piezoresistive sensors utilized isolation technology between the sensor network and the bulk underlying silicon based on the p-n junction. In these devices the individual piezoresistive gage elements were created via diffusion of p-type dopants such as Boron into the n-type substrate material in which electrons are the majority carriers. Although these devices were accurate and reliable at low temperatures, the p-n junction isolation broke down at higher temperatures – above 350° F[4]. Kulite began replacing the p-n junction approach with (SOI) Silicon on Insulator based technology over 40 years ago[5]. SOI technology enables the sensing elements to be dielectrically isolated from the substrate, and each other, via the use of a non-conductive isolation layer of silicon dioxide. This enables predictable and repeatable sensor behavior ranging from cryogenic temperatures all the way up to 1000°F and above[6].

Miniature piezoresistive and piezoelectric pressure transducers both support the measurement of high-frequency pressures and exhibit a wide dynamic signal range, but Kulite piezoresistive SOI devices are truly solid state devices as the force collector and sensing elements are all part of a monolithic silicon crystal structure. Piezoelectric sensors are a hybrid structure with bulk-material sensing elements mechanically linked to the force collector. Both types of transducers deliver excellent durability, good repeatability, and low hysteresis. Both technologies support the measurement of pressure at elevated temperatures (>250° F) provided integrated circuits are safely removed from excessive temperatures. Table 1 shows a comparison of Piezoresistive vs. Piezoelectric Technologies.

CHARACTERISTIC	PIEZORESISTIVE	PIEZOELECTRIC
Construction (see section 2)	Probe, Threaded, Flatpack	Probe, Threaded
Size (see section 3)	Probe: ≥ 0.055" diameter Flatpack: ≥ 0.025" height	Probe: ≥ 0.190 diameter
Overpressure Capability (see section 5)	2X to 50X	2X to 50X
Acceleration/Vibration Sensitivity - 100 PSI Sensor (see section 6)	≤ 0.00015 PSI/g	≤ 0.002 PSI/g
Operating Temperature Capability - Unamplified (see section 7)	-320°F to 1000°F	-320°F to 1040°F
Operating Temperature Capability - Amplified (see section 7)	-100°F to 400°F	-100°F to 275°F
Static Pressure Capability (see section 9)	Yes	No
Dynamic Response (see section 9)	≤ 1 µS rise time	≤ 2 µS rise time
Sensitivity Output - Unamplified (see section 10)	100 mV FS typical	Charge Output 25pC/Bar typical
Sensitivity Output - Amplified (see sections 10, 14)	0 to 5/10 V, 4-20 mA live offset optional – nominally 0.5 V	IEPE ± 5V
Drift (see section 10)	≤ 0.1% FS/year	≤ 0.5% FS/year
Total Error Band at Constant Temperature (see section 10)	≤ ± 0.1% FS typical	≤ ±1% FS typical
Dynamic Range (dB) (see section 10)	> 100 dB	> 100 dB
Thermal Effects (see sections 11, 12)	± 0.001 – 0.01% FS/ºF	± 0.03 – 0.2% FS/ºF
Cabling Requirements (see section 13)	4-conductor shielded or twisted pair (inexpensive)	Low noise coax (expensive) IEPE – coax (inexpensive)
Excitation Requirements - Unamplified (see section 14)	2-15 volts,10 volts dc typical	Self-generating
Excitation Requirements - Amplified (see section 14)	3.3 – 36 volts (unregulated)	2 – 20mA (constant current)
Cost (Transducer) (see section 16)	$500 to $1800	$650 to $6200
Cost (Equipment) - 50 ft./cable + conditioning (see section 16)	$75 to $1600	$400 to $3300

Table 1

2. *Sensor Construction and Installation:*

Piezoelectric type transducers are commonly constructed using natural or synthetic quartz crystals in a compression mode configuration as shown in Figure 1. The compression mode construction results in a rigid structure. These designs orient the piezoelectric crystal between a seismic mass and a rigid mounting base. This assembly is secured to the force collecting diaphragm by means of a preload screw. When the pressure on the diaphragm changes, an increase or decrease in the amount of compressive force acting on the crystal occurs resulting in a proportional electrical output.

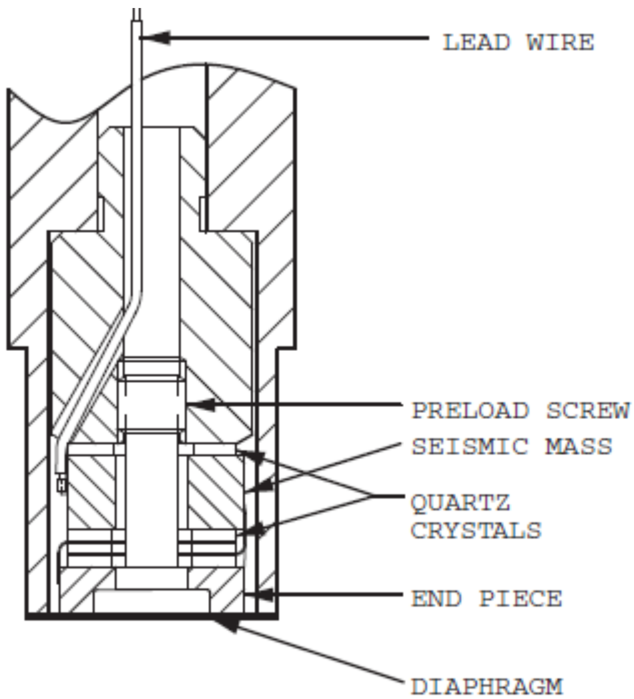


Figure 1: Compression Mode Piezoelectric Pressure Transducer

The high degree of stiffness provided by the compression mode enables the measurement of relatively high frequencies, but this construction worsens low frequency response due to thermally induced errors as will be discussed later. Additionally, the compression mode construction is susceptible to a form of zero shift[7]. Failure of the preload screw to maintain a constant force between the mass and the element will result in an output error. An abrupt change in the preload force may not be a one-time event and the resulting level shifts will be impossible to discern from pressure data.

Pressure transducers constructed using the compression mode can also be quite sensitive to installation. Virtually all miniature piezoelectric pressure transducers are constructed within a threaded assembly or a case requiring a threaded mounting adapter. If excessive torque is applied during transducer installation or if the sealing surface is improperly machined, the body of the sensor may become distorted and the sensitivity of the device will be affected. All piezoelectric pressure sensors are susceptible to some degree of degraded performance as a result of excessive mounting torque. The user is expected take special precautions to apply the manufacturer-recommended torque during installation.

Due to the small size of the pressure sensing silicon sensor, piezoresistive transducers may be constructed in a variety of packaging options that have been designed to eliminate the case-mounting effects on bias and sensitivity as well as low-frequency output generated by thermal expansion following proper installation. Piezoresistive SOI Sensors are fully integrated, monolithic structures. Figure 2 details the typical probe configuration of a piezoresistive pressure transducer.

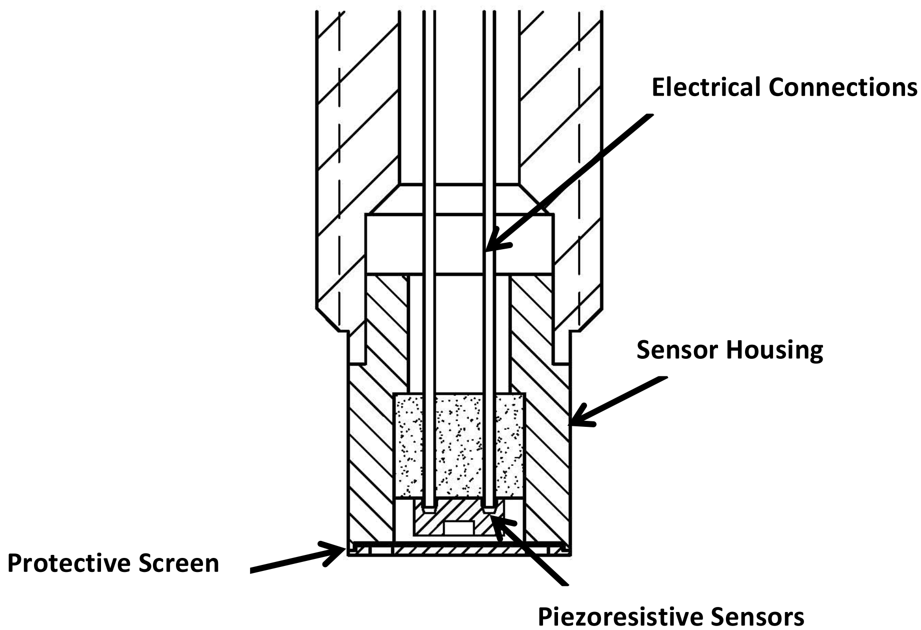


Figure 2: Piezoresistive Pressure Transducer Example

3. Size

The final form factor of a transducer is one of the more important device attributes for many customers. Kulite's SOI piezoresistive sensor technology offer more flexibility in packaging than any other technology due to the extremely small size of the sensing element. Automotive applications include engine air, oil, cooling and fuel systems, brake systems, transmissions and general laboratory/developmental pressure measurements. Typical aerospace applications are scale-model and full-scale flight tests. Scale-model wind tunnel test articles, for instance, require the measurement of pressures on leading edge portions of the airframe where the radius can be under one tenth of an inch. In other applications, pressure measurements must be made in areas where the test article thickness is very thin and cannot be penetrated. Only piezoresistive pressure transducers may be manufactured to small enough sizes to support either of these installations. Several SOI piezoresistive pressure transducers are currently manufactured having diameters of less than half that of the smallest commercially-available piezoelectric pressure transducers. The small size allows researchers to increase the density of measurements on a test article in critical areas, thus increasing the fidelity of the database developed to support future flight test programs.

Another way of increasing the density of pressure measurements is through the use of multi-channel pressure transducers. These multi-channel sensors are constructed within a single housing using two independent transducers with separate electrical outputs. Multi-channel sensors can be used to give increased reliability by allowing continuity of process control or the ability to shut the process down in an orderly manner if a single sensor were to fail. Reducing the number of sensor penetrations and wiring harnesses also has the benefit of decreased design complexity, fabrication, installation, maintenance, and repair costs.

The smallest commercially available piezoelectric pressure transducer is 0.9 inches in length, 0.19 inches in diameter, and has an active sensing region 0.099 inches in diameter. The electrical ground return is made to the sensor body for the smallest piezoelectric pressure transducers. When installing these pressure transducers to electrically conductive surfaces, a potential exists for the entry of noise into the ground path of the measurement signal through the transducer case. Typically, the addition of ground-isolating hardware that increases the overall size of the transducer bore is installed to prevent the generation of ground loops due to differing electrical potential between the transducer and the signal conditioning equipment.

Kulite can provide an isolated piezoresistive pressure transducer 0.375 inches in length, 0.055 inches in diameter, and having an active sensing element that is approximately 0.035" x 0.035". This means that the smallest piezoresistive sensor is an order of magnitude smaller in volume, weight and sensing area. Alternately, Kulite can provide low-profile flat transducers that are no taller than 0.030 inches. The range of packaging options provided by Kulite is unequaled in the pressure transducer industry. Kulite is synonymous with miniature pressure transducers. Customers have given Kulite the ultimate compliment by using the brand name "Kulite" to define the entire product category.

4. *Extreme Environments Operability/Ruggedness*

While piezoelectric transducers are suitable for many extreme environment applications, commercially available piezoelectric pressure transducers use sensitive elements which are cut from bulk crystal material. The resulting relatively large-sized component provides a level of durability sufficient for a significant number of extreme environment applications.

A majority of harsh environment commercial applications use piezoresistive pressure transducers due to the small sensing element size ($\approx 0.25 \times 10^{-6}$ $inch^3$ in volume), miniscule mass, and robust construction (see section 3). Piezoresistive pressure transducers do not require external amplifiers and special cables (see section 13) that other technologies need. Kulite routinely customizes piezoresistive transducers to match a customer's particular requirements for applications in specific environments, and these devices operate well in aircraft engine, nuclear, downhole, cryogenic, space, motor sports, and other extreme environment pressure measuring applications. Kulite piezoresistive pressure transducers have been tested by customers and proven to exhibit over 1 million hour MTBF (mean time between failure) in various aerospace and industrial applications.

When considering all pressure measurement applications, piezoresistive pressure transducers exhibit superior performance to their piezoelectric counterparts in terms of their ruggedness and their ability to operate reliably in harsh environments.

5. Overpressure Capability

The range of the pressure transducer specifies the recommended maximum peak pressure level for optimum linear response. Most Kulite pressure transducers maintain good linearity up to 3 times the range (proof pressure), and temporarily exceeding the rated pressure does not affect performance beyond specified tolerances. This is intended as a safety margin, not for normal use. Kulite pressure transducers typically provide a safety factor of at least 2 times the rated pressure for lower range transducers. High-pressure ranges are somewhat derated and it is best to verify proof and burst pressure prior to installation. Pressure chip designs having an internal mechanical stop to limit the deflection of the diaphragm can withstand considerably higher pressure of up to 50X the rated pressure in some instances. Stopped Kulite transducers recover from an overload condition immediately.

Piezoelectric pressure transducers are constructed in a compression mode and can typically tolerate 10X overpressure without adverse effects depending on the pressure range, size, and sensitivity. Unlike stopped piezoresistive pressure sensors, piezoelectric pressure transducers take a discrete amount of time to recover from an overpressure condition or a transient shock event. Generally, miniature piezoelectric pressure transducers are limited to lower pressures (to 2X range) and larger piezoelectric pressure transducers can tolerate higher pressures (to 50X range). However, piezoelectric pressure transducers are incapable of absolute pressure measurement. Users may therefore be unaware they are operating in a region outside the recommended pressure range. For all pressure transducers, it is best to limit dynamic pressure to frequencies of 30% of resonance frequency. Approaching the diaphragm resonant frequency will result in erroneous data and may lead to diaphragm failure.

6. Acceleration/Vibration Sensitivity

The acceleration sensitivity of a pressure transducer is defined as the maximum difference, at any pressure level within the specified range, between output readings taken with and without the application of a specified acceleration along a specified axis.

Kulite's pressure transducers, by design, are highly insensitive to acceleration inputs. The reaction of the silicon diaphragm to acceleration is a function of its stiffness, mass, thickness and diameter. In the case of a Kulite pressure transducer, the active area of the silicon diaphragm is extremely small, has a low mass and is very stiff. When combined, these characteristics result in a pressure transducer which is not only physically very small, but also has a very low sensitivity to both acceleration and vibration.

Sensitivities as low as 0.00003 % FS/g are available in the pressure sensitive direction which is normal to the plane of the diaphragm. For example, for a 1000 g in-axis (worst case) acceleration input the total error might be as low as 0.03% full scale. Cross acceleration sensitivities (accelerations parallel to the plane of the diaphragm) are generally between a 1/5th and a 1/10th of the sensitivity in the pressure sensitive direction. Kulite typically specifies the acceleration/ vibration sensitivity for different pressure ranges on individual data sheets and these are typical values from sample tests.

For application in extremely high acceleration or vibration environments, Kulite has designed an acceleration compensated pressure sensor which has a negligible acceleration sensitivity even when subjected to accelerations in excess of 60,000g. The acceleration compensated pressure sensor is based upon leadless technology and is capable of operation in high temperature. Piezoelectric pressure sensors generally show a high sensitivity to acceleration and vibration inputs due to the relatively large size and high mass of the piezoelectric elements. Sophisticated pressure sensors therefore are compelled to use acceleration compensation elements in addition to the pressure sensing elements in order to ensure that the pressure transducer only responds to a pressure input. By carefully matching these elements, the acceleration signal (released from the compensation element) is subtracted from the combined signal of pressure and acceleration to derive the true pressure information. The need to include acceleration compensation crystals results in a pressure transducer which is significantly larger and heavier than its corresponding piezoresistive counterpart. A typical acceleration compensated, piezoelectric pressure transducer will have a pressure sensitivity of 0.001% FS/g. When subjected to an acceleration/ vibration of 1000g, the transducer will generate a non-pressure related output of 1.0% full scale, which is in the approximately 33 times greater than a piezoresistive pressure transducer when exposed to a similar acceleration/ vibration level.

7. Temperature Capability

The high temperature limit of charge mode transducers is set by the Curie temperature of the piezoelectric material or by the properties of insulating materials employed in the specific design. A limited number of rare, naturally occurring crystals and lab-created synthetic crystals can exceed the operating temperature range of SOI pressure sensors. Piezoresistive pressure sensors constructed using the SOI process can withstand continuous temperatures of 1000° F whereas the extreme temperature charge mode piezoelectric pressure transducers can support measurements to 1040° F. However, this is a special case and unamplified piezoresistive pressure sensors generally can operate at higher temperatures than most charge mode piezoelectric pressure transducers.

Natural tourmaline crystals are pyro electric. They accumulate charge with changes in temperature as well as force. The crystalline elements therefore produce spurious output when undergoing temperature changes. As a naturally occurring crystal, tourmaline has inherent inclusions and defects, resulting in non-repeatable charge output as force is applied. Other high temperature piezoelectric sensors are based on man-made materials. The oxide compounds of these crystals release oxygen at high temperatures, thereby resulting in a decrease in electrical impedance with increase in temperature. Transducer manufacturers attempt to compensate for oxygen loss by using larger crystals.

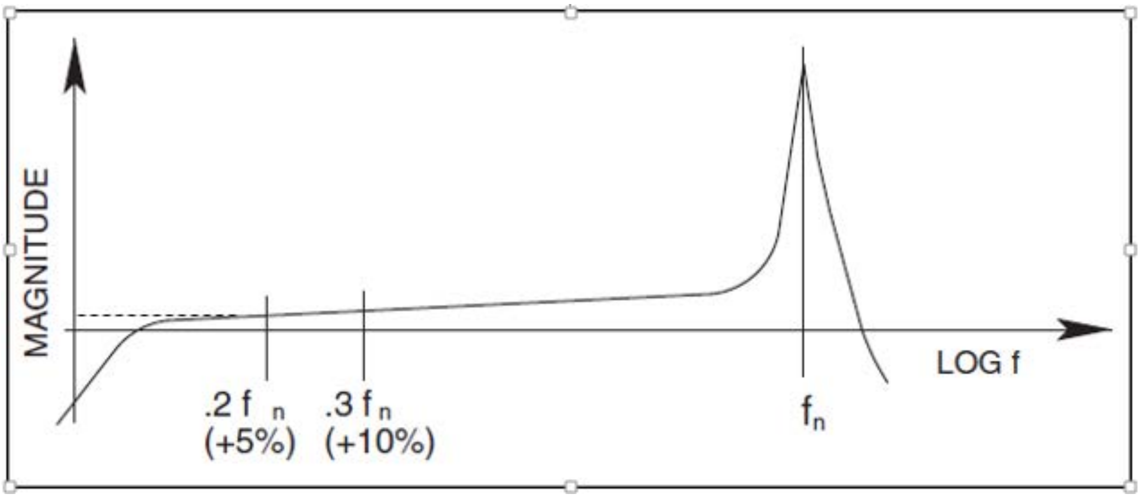
Quartz is naturally piezoelectric and is considered the most stable of all piezoelectric materials, but the temperature range of quartz is limited to approximately 600° F. Due to the low charge sensitivity of quartz, its usefulness in charge-amplified systems, where low noise is an inherent feature, is limited. As a consequence, quartz piezoelectric pressure transducers are most often configured as IEPE transducers.

Charge converter electronics, IEPE transducers, and amplified piezoresistive pressure transducers are generally limited to 275° F. Kulite has developed embedded electronics for amplified pressure transducers that are rated for continuous operation to 400° F (or above). Kulite has also introduced a line of Silicon on Insulator (SOI) electronics suitable for operation up to 500°F thus increasing the temperature capability of some amplified transducers to these temperatures[8].

8. *Frequency Range (Static and Dynamic Operation)*

Frequency response is the characteristic amplitude/phase response of a sinusiodally applied input pressure. The usable frequency range is not to be confused with the natural frequency (resonance) of the sensor, but the two are related. Most transducer manufacturers apply the "rule of thumb" that a measurement error of approximately 5% is present at 20% of the natural frequency. This error typically rises to a 10% error at 30% of the natural frequency. See Figure 3 for an example of the advertised frequency response of a typical piezoelectric pressure transducer.

In addition to the resonant frequency of the sensing element, the usable frequency response or bandwidth of a transducer is dependent on the size of the sensing diaphragm and its orientation to the pressure wave[9]. Pressure transducers have a finite diaphragm size that effectively averages the pressure across it. This pressure averaging or spatial resolution results in an attenuation of dynamic pressure signals with increasing frequencies as the wavelength of the pressure wave approaches the diameter of the sensor's diaphragm. As illustrated by Figure 4, the angle of incidence is defined as the angle between the axis of the diaphragm and the approaching sound wave. When the pressure wave approaches at a 0° angle of incidence, spatial averaging is less of a concern, assuming the wave is relatively uniform in space, as the wave will strike the diaphragm uniformly in space and time. However, at a 90° angle of incidence, pressure waves will vary in amplitude across the diaphragm resulting in attenuation based upon the frequency of the wave and diameter of the diaphragm.



*Note: Dashed line indicates corresponding Piezoresistive Transducer Frequency Response

Figure 3: Piezoelectric Pressure Transducer Frequency Response

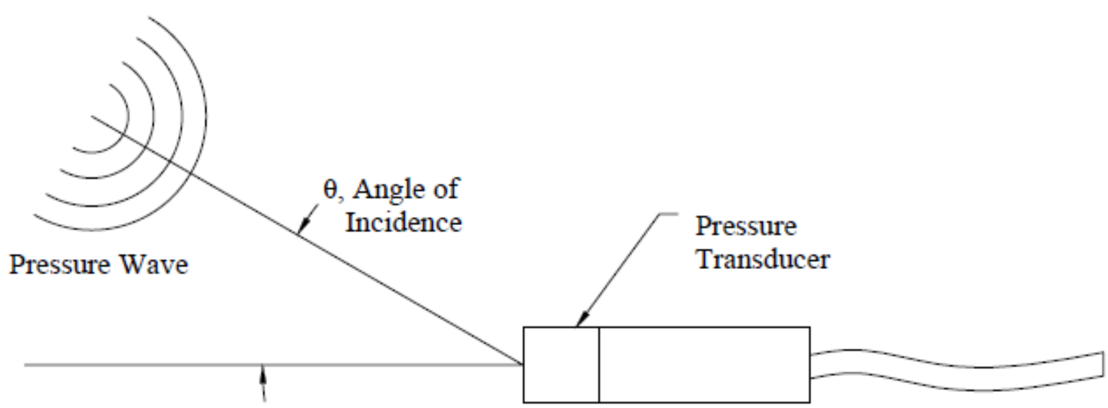


Figure 4: Sound wave angle of incidence

The force collecting diaphragm can be made much smaller in piezoresistive pressure transducers than in piezoelectric pressure transducers. Figure 5 shows the estimated amplitude and phase response of various transducers with diameters ranging from 0.062” to 0.25” assuming response to 0 Hz. This spatial resolution analysis assumes that pressure waves are traveling at a constant speed of sound. Attenuation increases with higher temperature due to the corresponding increase in the local speed of sound. In some applications, such as blast testing, changes in local temperature a great enough that significant change in the local speed of sound take place. As Figure 5 indicates, averaging of higher-frequency pressures by force-collecting surface results in attenuation and a phase shift which increases as the sensor diameter increases. This effect is not typically reported by pressure transducer manufacturers.

Kulite piezoresistive sensors are inherently small (on the order of 0.035” x 0.035” x 0.013”) giving Kulite the unique ability to manufacture transducers having diameters of 0.055” and smaller. Pressure diaphragms of this size are required to accurately measure dynamic pressures traveling parallel to the diaphragm to 50 kHz and above. Conversely, piezoelectric pressure transducers with diameters of 0.218” are advertised to have natural frequencies of 500 kHz leading the customer to believe that frequencies up to 100 kHz may be observed. This is simply not the case as indicated by the estimated frequency response of 25 kHz in Figure 5.

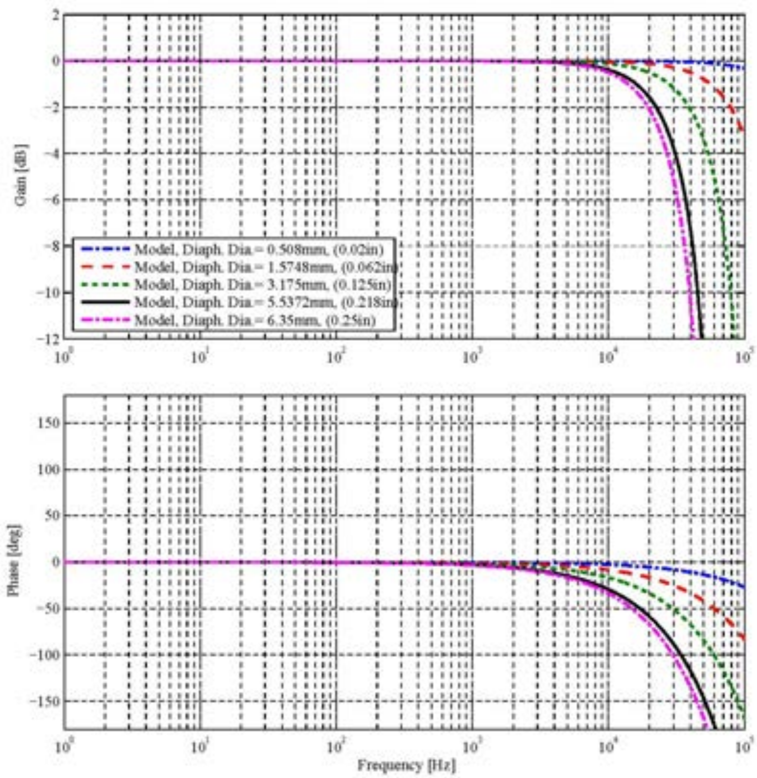


Figure 5: Effects of Spatial Averaging on Amplitude and Phase

Rise time specification is also a method used to convey the responsiveness of a pressure transducers. Rise time is the time required for the output to rise from a small percentage (10%) to a large percentage (90%) of its steady-state value, when excited by a step change in pressure[10]. The rise time of pressure transducers has historically been estimated via a unit step input in pressure created through a shock tube test. Data from this test are also used to determine the pressure sensor damping ratio and damped natural resonance of the pressure chip. Size and geometry of the diaphragm have a similar effect to frequency response on the transducer rise time, but not its natural frequency.

Cabling and electronics also play an important part in the frequency response of pressure transducers. The drive current of IEPE transducer signal conditioners or remote charge converters (used with charge mode devices) is normally set from 2 mA to 5mA and may be increased up to 20 mA in order to extend the frequency response of piezoelectric pressure measurements. An increased drive current increases the slew rate and minimizes signal distortion from the transducer, but a serious consequence of this technique is the associated self-heating of the internal miniature amplifier that will cause bias shifts at all frequencies[11]. Use of this technique should be limited to lower temperature installations as the additional thermal stress on the internal amplifier will shorten the life of the IEPE transducer or remote charge converter. Alternately, less sensitive devices may be installed to limit the voltage output. Lower level signals are less susceptible to distortion at higher frequencies at a cost to the overall signal-to-noise ratio of the measurement.

The bandwidth of piezoresistive sensors is fundamentally dependent on sensor output impedance and cable capacitance to the amplifier or measurement system. High frequency operation is typically supported using high-quality cable and/or by embedding the amplifier in the transducer body or by placing the transducer amplifier in-line with the cable. Typically a 10X to 20X improvement is seen in the frequency response of long cable runs when an amplifier is placed in close proximity to the transducer. Kulite offers a number of amplifier options up to a maximum bandwidth of 150 kHz.

Piezoelectric sensors are effectively AC coupled devices, and as such, are incapable of measuring a true static pressure as piezoelectric material can only sense alternating force. Some lower frequency measurements (<0.5 Hz) are possible using piezoelectric transducers, but the user must be aware of current drive and associated self-heating causing drift in the output of the transducer during low frequency operations. Piezoresistive sensors offer true static pressure measurement capability without taking any special precautions.

9. *Sensitivity/Output*

The sensitivity of a piezoresistive pressure transducer is defined as the ratio of its electrical output to its mechanical input. Sensitivity is usually presented as 100 mV at full scale pressure for an excitation level of 10 volts DC. There is a linear relationship between excitation voltage and transducer sensitivity. Sensitivity may be scaled up or down by varying the fixed excitation voltage between 5 volts and 12 volts. The excellent repeatability, stability, and linearity of the Kulite pressure transducer output enables an accuracy improvement of 10X to 20X over that of piezoelectric pressure transducers. This performance characteristic is the single most important parameter when considering the achievable measurement accuracy.

Sensitivity for a charge mode piezoelectric pressure transducer is typically expressed in picocoulombs (1×10^{-12} coulombs) per PSI. All charge mode piezoelectric pressure transducers must rely on specialized measurement equipment to transform the small amount of electrical charge generated by the stressed crystals into a voltage signal compatible with data acquisition systems while inducing minimal changes to the original information. A laboratory-grade charge amplifier costing $3,000 or more is used to perform this function in many installations.

The sensitivity of voltage mode piezoelectric (IEPE) pressure transducers is expressed in the more familiar terms of millivolts per PSI. Unlike the charge mode transducer, the IEPE pressure transducer utilizes the voltage signal generated by the piezoelectric element rather than the charge signal. Voltage sensitivity and the discharge time constant are established at the time of final assembly, setting the full scale range and low frequency response respectively. The voltage sensitivity of the IEPE pressure transducer is adjusted by the manufacturer by varying the total capacitance spanning the piezoelectric element. Voltage sensitivity is typically attenuated by adding capacitance or maximized by omitting additional capacitance across the element. Voltage sensitivity cannot be altered after final assembly.

Most properties of a piezoelectric elements erode with a logarithmic relationship with time. Exact rates of aging depend on the composition of the element (ceramic, man-made crystal, or natural crystal) and the manufacturing processes used during fabrication. Mishandling the element by exceeding its electrical, magnetic, mechanical, or thermal limitations can accelerate this inherent process. A general "rule of thumb" is that sensors using ferroelectric crystal elements will likely experience a sensitivity loss of less than 0.5% per year. Crystalline elements can also experience sensitivity loss over time, but generally perform better than ceramic elements[12].

Monocrystalline silicon provides very high mechanical strength and near perfect elastic behavior up to the point of mechanical failure. Formation of piezoresistors is accomplished by replacing a low percentage of silicon atoms with electrically active atoms. The result is a sensor with monolithically integrated single crystal silicon resistors that exhibits nearly imperceptible hysteresis and non-linearity because the mechanical properties of the silicon material are unaltered. The semiconductor resistors are joined together in a bridge configuration via conductive pathways. The resistors are placed on the diaphragm such that two experience mechanical tensile stress and the other two experience compressive stress as the diaphragm is responds to pressure. Thus, with proper placement the two pairs exhibit resistance changes equal and opposite to each other. Silicon piezoresistors are precisely placed in a Wheatstone bridge configuration on a micro-machined single crystal silicon diaphragm. The sensitivity of piezoresistive pressure transducers is typically proportional to the applied pressure within ±0.1% of full scale or better with excellent long-term stability.

10. Dynamic Range

Dynamic range is the range of pressure values which a transducer is intended to measure, specified by upper and lower limits. Equation 1 is used to determine the dynamic range of a pressure transducer whose full scale output response is V_{FSO} and whose noise floor is V_{NOISE}. The noise floor is usually estimated over a 20 kHz bandwidth and is expressed as the signal-to-noise ratio (SNR) in decibels (dB).

Equation 1: $$SNR(dB) = 20*\log_{10}(V_{FSO}/V_{NOISE})$$

Kulite pressure transducers have been estimated to exhibit a dynamic range of 114 dB at room temperature (V_{NOISE} is a function of temperature)[13]. The major noise sources in piezoresistive sensors are 1/*f* noise caused by conductance fluctuations and thermal Nyquist-Johnson noise caused by thermal agitation of electrons in the conductor. For doped silicon piezoresistors, the dynamic range can be on the order of 120 dB, but both the resistance and gauge factors of piezoresistors are sensitive to thermal variations as Nyquist-Johnson noise increases with temperature. [14]

Charge mode accelerometers may have a signal-to-noise ratio approaching 120 dB, but the installation is susceptible to extraneous noise pickup from vibrating cable and moist or dirty environments. Most commercially available IEPE pressure transducers report dynamic ranges from 95 to 105 dB. These reported levels worsen when higher levels of constant current power are supplied. When properly installed, both piezoresistive and piezoelectric pressure transducers possess a dynamic range compatible with higher order dynamic data acquisition systems having 16 bits of resolution or higher. A high resolution A/D converter is required to identify small pressure levels over the bandwidth of interest. The accuracy levels associated with such data systems is somewhat lost when to interfaced to piezoelectric pressure transducers having a total error band 10X to 20X higher than that of piezoresistive pressure transducers.

11. Thermal Effects

The maximum operating temperature of a charge mode sensor is limited by the Curie point of the piezoelectric material. The piezoelectric element will begin to depolarize at temperatures above the Curie point causing a permanent loss in sensitivity. A typical specification for maximum operating temperature is the temperature at which the permanent change of sensitivity exceeds 3%. Charge mode piezoelectric pressure transducers that have been subjected to temperatures at or near the Curie point of the sensing element should be recalibrated to obtain the new sensitivity coefficient before use.

All pressure transducers are sensitive to thermal shock from the pressure media. Piezoelectric pressure transducers, in particular, exhibit unsteady low frequency output when subjected to thermal transients due to their compression mode construction and due to the variety of materials used in their construction. Different coefficients of expansion of internal materials lead to the production of spurious outputs. These effects typically result in perceived pressure fluctuations at frequencies lower than 10 Hz. It is recommended to limit the low frequency response of the piezoelectric pressure transducer measurement system when thermal transients are expected.

When heat is applied the case of the piezoelectric transducer instead of the diaphragm, the subsequent expansion of the case can lower the preload force and generate a false negative transient pressure output. Similarly, false positive transient pressure outputs are generated when heat leaves the piezoelectric transducer as the mounting structure cools. Correction of these erroneous signal levels due to thermal shock cannot be accomplished by the application of a temperature-corrected sensitivity coefficient. It is best to avoid the use of piezoelectric pressure transducers for low frequency pressure measurements entirely unless the specimen temperature can be controlled. In extreme conditions, rapid temperature changes will permanently damage the piezoelectric crystals due to large gradients across the rather bulky sensor stack.

In general, piezoelectric material will be exhibit a non-linear sensitivity versus temperature curve. Temperature sensitivity coefficients for piezoelectric pressure transducers typically range from 3X to 20X higher than the more easily compensated piezoresistive pressure transducers. An example of non-linear temperature sensitivity for a man-made piezoelectric sensor is shown below in Figure 6.

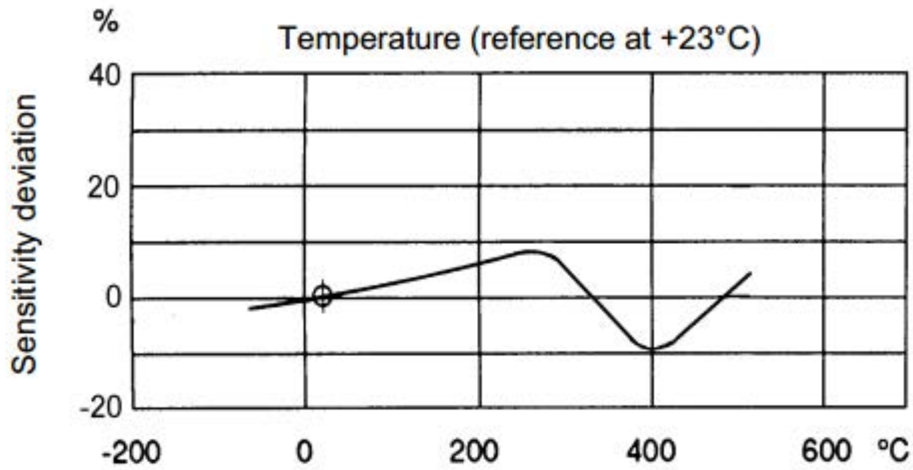


Figure 6: Example of Non-Linear Temperature/Sensitivity Curve

12. Temperature Compensation

The resistance of p-type silicon piezoresistors increases with temperature. Providing the temperature coefficient of the bridge resistance is greater than the temperature coefficient of gauge factor, it is possible to select a resistor which acts as a voltage divider in such a way as to increase the voltage at the bridge at a rate equal to the decrease in gauge factor with temperature. Span compensation is thus accomplished in piezoresistive pressure transducers by using a series resistor with constant voltage excitation to compensate for loss of strain sensitivity with increasing temperature. Worst case temperature sensitivity of monolithic silicon piezoresistive pressure transducers is typically presented as ±0.01% of full scale per degree Fahrenheit after appropriate passive compensation resistors have been selected and applied.

Alternately, piezoresistive pressure sensors may be conditioned by the use of embedded digitally-programmed electronics. The programmable analog sensor conditioner circuitry is paired with sufficient memory to linearize the piezoresistive pressure sensor to better than ±0.1% of full scale at a constant temperature. Since the bridge resistance changes predictably temperature and piezoresistive pressure sensors are extremely repeatable, the embedded electronics may also be used to correct for bias and sensitivity shifts due to temperature. Piezoresistive pressure transducer temperature sensitivity may be controlled to within ±0.001% of full scale per degree Fahrenheit after electronic characterization of the pressure sensor is programmed into the embedded conditioning electronics.

Limited temperature compensation of piezoelectric material is possible with the addition of an in-line capacitor for charge mode devices or a parallel capacitor for high impedance voltage amplification, but the sensitivity will be lowered in direct proportion to the decrease in capacitance. Alternately, the temperature coefficient of the transducer may be stated for several different operating temperature ranges.

13. Cabling Requirements

Specially treated cable costing about $1.50/ foot must be used to connect charge mode transducers to each associated charge converter or charge amplifier. This cable is manufactured with the inclusion of a graphite lubricant between the braided shield and dielectric core in order to minimize the triboelectric effect. The physical motion of the untreated coaxial cable will generate electrostatic changes that, when coupled with the exceptionally high gain of the charge amplifier, will generate spurious noise that cannot be distinguished from pressure produced signals.

Charge output pressure transducers may be used when high-temperature environments are anticipated. An in-line charge converter is normally placed as close to the transducer as possible to reduce installation costs and the potential for noise. In general, 250° F is the maximum temperature allowed for safe operation the in-line charge converter. It is important to connect the electronics to the sensor using coaxial cable because the input to a charge amplifier is at a very high impedance level and, as such, is susceptible to noise pickup if not continuously shielded.

The internal components of the pressure transducer and the electrical connector must maintain a very high insulation resistance throughout the transducer/charge converter signal path. In moist and dirty environments, it is necessary to provide additional environmental protection to the components and cabling to maintain this high insulation resistance. Protection of cable connections at the sensor and charge amplifier with waterproof heat-shrinkable tubing is often required. Any connectors, cables, or amplifiers that do not maintain the manufacturer's recommended insulation resistance will negatively affect the pressure measurement resulting in unpredictable drifting of the charge amplifier output[15]. The transducer may suffer degraded low-frequency response, reduced sensitivity and erratic output with unstable insulation resistance values at the input to the charge amplifier.

All piezoelectric pressure transducers exhibit decreased insulation resistance when exposed to elevated temperature. This effect is due in part to the piezoelectric element, but the mineral insulated cable necessary to withstand the high temperatures typically contributes the largest error source. Specially constructed charge amplifiers must be used that are designed to operate with low impedance systems. These instruments capacitively couple the charge amplifier to the transducer/cable system to minimize the impact of potentially large offset voltages.

The output of charge converters as well as IEPE compatible transducers do not require specially-treated, low-noise cables and can be connected to the constant-current power supply using a standard coaxial cable such as RG58/U. Coaxial cable length is rarely an issue, but the frequency response may be somewhat diminished in long cable runs. The power supply current may be increased to overcome attenuation at higher frequencies in these cases.

Amplified piezoresistive pressure transducers are normally connected to a measurement system using low-cost, 4-conductor, shielded, twisted pair cable. Unamplified piezoresistive pressure transducers may use either two-pair or three-pair cable depending on the length of cable. Three-pair, 6-conductor, is recommended to account for any loss of excitation. Each pair should be dedicated to a single function for maximum noise immunity: one twisted pair for excitation, one twisted pair for sense, one twisted pair for signal.

14. Excitation Requirements

All IEPE devices require active electronic circuitry that cannot be shared among other transducers. A miniature amplifier is embedded within the transducer package for constant current powered piezoelectric devices. An external conditioner is required to excite the transducer using constant current, remove the DC voltage bias from the signal, increase system gain, and filter the signal prior to connection to its measurement system.

Charge mode transducers connected to remote charge converters operate in a similar fashion, but the charge converter is physically separated from the transducer with low-noise coaxial cable of 50 feet or less. The sensitivity of the transducer may be set in fixed increments by switching various values of feedback capacitor into the feedback path of the amplifier. The charge converter electronic components cannot be exposed to temperatures in excess of 250° F. The resulting output may be interfaced to a constant current conditioner as described above for the IEPE case.

As mentioned earlier, the miniature amplifier used in IEPE transducers has limited heat dissipation properties. Constant current power should be minimized to keep junction temperatures low in order to lessen background noise and to prolong the life of the device. This is especially important when the sensor is used at elevated temperatures close to the 250° F maximum allowable temperature. A tradeoff between higher frequency response and lower signal-to-noise ratio of the IEPE transducer or charge converter should be evaluated for each installation.

Piezoresistive devices supplied with an appropriate bridge excitation (normally 2 to 15 volts, constant voltage) generate a significant, measurable voltage on the signal leads as the physical stimulus is varied. For cost-sensitive installations, multiple unamplified transducers may be powered using a single, regulated excitation source provided each pair of signal leads is interfaced to a differential amplifier or A/D input. Alternately, lab-grade constant voltage signal conditioners may be employed per transducer to provide sophisticated amplification, filter, and in-place calibration capability ahead of the measurement system.

Internally amplified piezoresistive devices can share a single power supply as well, but the supply voltage regulation is not critical. Amplified piezoresistive transducers typically contain embedded internal voltage regulation, amplification, and output filters. Limiting the voltage with increased temperature is not required as amplified piezoresistive pressure transducers contain circuitry to isolate and regulate the optimum internal power levels. Amplified piezoresistive transducers may be connected directly to the measurement system input in many cases without the need for any external conditioning electronics. This approach is commonly used to minimize the quantity of supporting equipment.

Constant current amplified piezoresistive transducers (commonly known as 4 to 20 mA transmitters) are used when long cable runs are required. This 2-wire interface is common for industrial applications and offers some advantages including noise immunity, transmitter/cable fault detection, and is insensitive to wire resistance ranging to several hundred ohms. Constant current transmitters are generally used in lower frequency applications. This interface is not to be confused with the 2 to 20 mA constant current IEPE power supply.

15. Amplifier (Signal Conditioning) Requirements

Many applications employing charge mode transducers utilize a lab-grade charge amplifier that offers multiple analog domain functions such as amplification, filtering, integration (for velocity and displacement), RMS/DC, phase tracking or peak hold options prior to connection to its measurement system. Lab-grade charge amplifiers also are used to standardize pressure sensitivity to levels such as 50 mV/PSI. Standardization is often desirable as charge mode transducers cannot be made to precise sensitivities. For some uses, it is recommended to use a good-quality strain gage signal conditioner/amplifier when interfacing to unamplified piezoresistive pressure transducers for many of the same reasons.

IEPE transducers and remote charge converters require the use of a constant current supply/conditioner. Many of these devices include fixed gain steps and some output filter options for treatment of the signal that is interfaced to the measurement system. Amplified piezoresistive pressure transducers may be interfaced directly to the input channel of an A/D converter without the need for an external amplifier/conditioner provided the A/D converter contains an internal anti-alias filter. Flexibility may be improved by interfacing an amplified transducer to an external signal conditioner in select applications.

16. Cost

Installation costs of measurement systems dedicated to piezoresistive pressure transducers are generally lower than systems designed for piezoelectric pressure transducers. Transducers, cabling, and electronics for piezoresistive pressure transducers are each less than the cost of the corresponding piezoelectric pressure transducer system component. Fewer individual components are also a characteristic of piezoresistive pressure transducer installations.

Charge mode piezoelectric transducers are employed when temperatures above 250° F will be encountered or when the features of a lab-grade charge amplifier are desired. Per channel cost of lab-grade charge amplifiers can cost well over $3,000. Extreme-temperature charge mode piezoelectric pressure transducers commonly cost more than $6,000 resulting in a single measurement channel cost of approximately $10,000 (not including the A/D converter). The comparable cost of the high-temperature piezoresistive pressure transducers is $1800 for the transducer and $1500 for the strain-gage conditioning electronics.

A lower cost method of utilizing charge mode pressure transducers with remote charge converters and IEPE constant current power supplies can be employed in some cases. The constant-current piezoelectric power supply is a fraction (nominally $300 for multi-channel systems) of that for the lab-grade charge amplifier. The cost for this architecture (remote charge converter and constant-current power supply) is approximately $1000 per channel plus the cable costs of $1.50/foot and the cost of the transducer, but the benefits of the lab-grade charge amplifiers are lost.

In order to approach the single channel cost of piezoresistive pressure transducer installations, IEPE transducers limited to 250° F must be utilized. IEPE pressure transducers require the constant-current piezoelectric power supply and low-cost coaxial cable for proper operation. With proper A/D converter selection, no additional conditioning electronics are required when amplified piezoresistive transducers are installed. Piezoresistive pressure transducers generally offer that most flexibility and capability while maintaining lower overall installation cost.

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