PRESSURE FUNDAMENTALS

PCB PIEZOTRONICS
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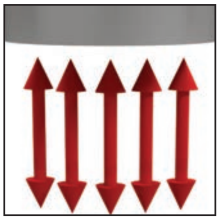
ICP® & CHARGE PRESSURE SENSORS

THEORY OF OPERATION

Piezoelectric pressure sensors measure the dynamic pressure resulting from turbulence, cavitation, blast, ballistics, and engine dynamics. They incorporate piezoelectric sensing elements with a crystalline quartz atomic structure which outputs an electrical charge when subjected to a load with near zero deflection. The charge output occurs instantaneously, making them ideal for dynamic applications but subject to decay and therefore not capable of static measurements.

PCB® pressure sensors utilize an upper electronics section and a lower sensor section. The electronics section contains the electrical connector, potting, lead wire, and ICP® amplifier, if equipped. The sensing section includes a stack of disc-shaped sensing elements preloaded in compression between upper and lower masses that are retained by an outer preload sleeve. A diaphragm welded to the outer housing retains the pressure and transfers the pressure loading to the mass / element stack to generate the piezoelectric charge. An external mounting clamp nut provides positive retention for the sensor and loads the seal ring for a high pressure seal. PCB pressure sensors are exceptionally stiff with good frequency response while isolating the media from the sensing elements.



TWO MAIN TYPES OF PRESSURE SENSORS

- ICP® - Identifies PCB sensors that incorporate built-in microelectronics. The ICP® electronics convert a high-impedance charge signal generated by a piezoelectric sensing element into a usable low-impedance voltage signal when powered with constant current. The modified signal can be readily transmitted over two-wire or coaxial cables to data acquisition systems or readout devices.

- Charge mode - The output of a charge mode pressure sensor is a high impedance signal which is dependent on electrical insulation for low loss / low noise transmission. It should be converted to a low impedance signal prior to the data acquisition system (DAQ) or readout device. It is important to use low noise cables and avoid using cables with insulation damage or contamination.

ICP® ADVANTAGES

- Simple to operate
- Able to operate in dirty environments over long cable runs
- Uses integral power from all manufacturers' data acquisition systems (may require specific module)

ICP® DISADVANTAGES

- Maximum operating temperature of 356 °F (180 °C)
- Sensitivity and low frequency response are not adjustable
- Requires ICP® constant-current power

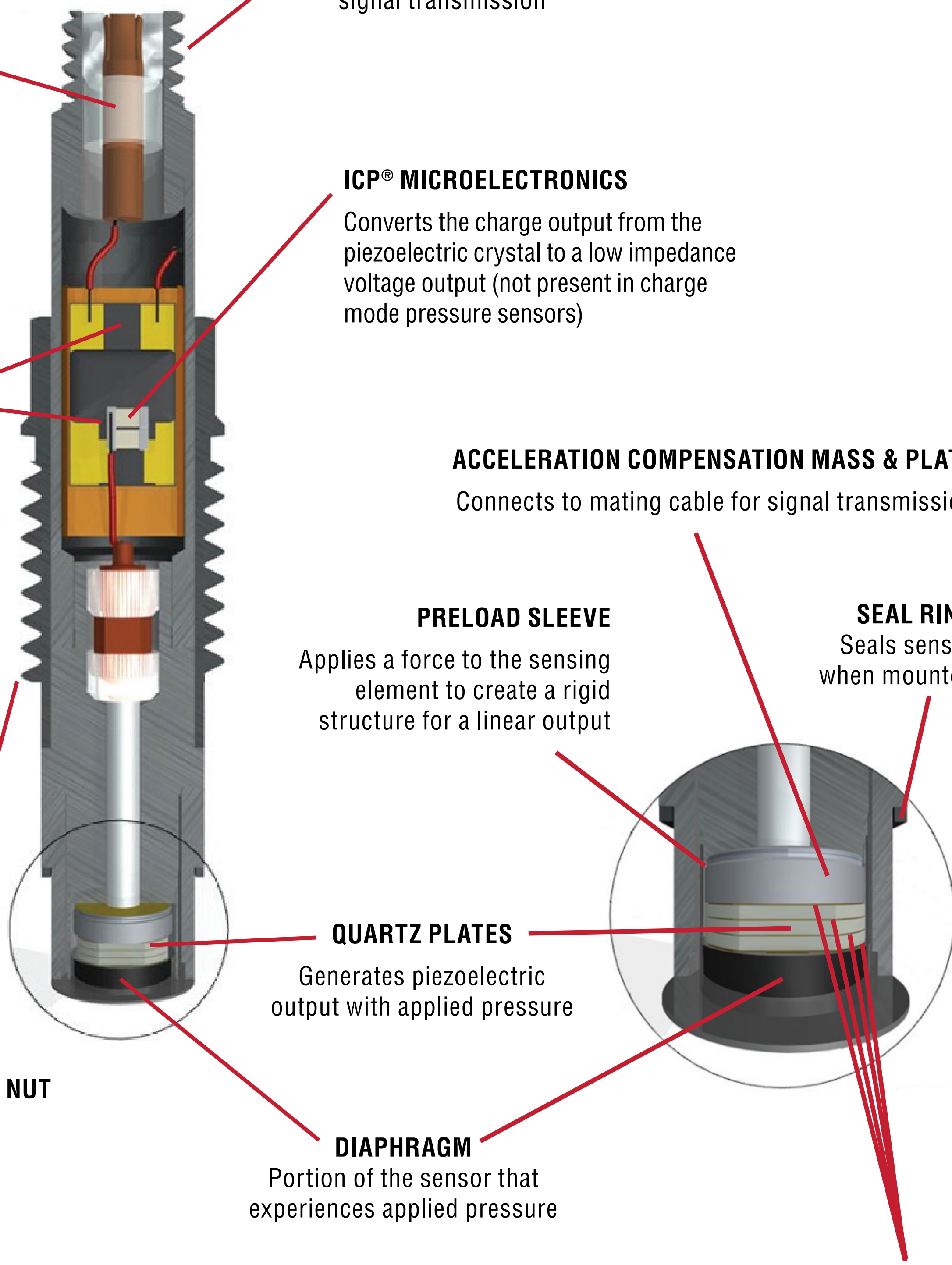
CHARGE MODE ADVANTAGES

- Operating temperature up to +1,200 °F (+650 °C) for UHT-12™ element with hardline cable
- Flexibility in adjusting sensor output characteristics
- Extended low frequency response with long time constant charge amps

CHARGE MODE DISADVANTAGES

- Additional cost of required charge amplifier or charge converter
- Sensor and cable connections must be kept clean and dry for best performance
- Requires a more costly, low noise cable

TYPICAL PCB® PRESSURE SENSOR



ELECTRONICS FOR ICP® & CHARGE PRESSURE SENSORS

ICP® PRESSURE SENSOR INSTRUMENTATION

ICP® pressure sensors must be powered from a constant-current DC voltage source (see specific sensor datasheet for turn-on voltage). Once powered, the electronics within an ICP® sensor convert piezoelectric charge to a low impedance signal with power and output on the same channel. ICP® signal conditioners or ICP® configured readout devices will remove the power portion of the signal, resulting in full scale output of ± 5 volts.

PCB offers multiple ICP® signal conditioners from 1 to 16 channels with current adjustment within 2 to 20 mA at +18 to +30 volts DC. Refer to PCB Tech NoteTN-32 for more information on signal conditioners and impedance. Do not attempt to power ICP® sensors with commercially available power supplies as unregulated current will damage the sensors' internal electronics.

ICP® Pressure Sensor

General Purpose Cable

Signal Conditioner for ICP® Power
(Conditioned output to Oscilloscope or DAQ)

When a data acquisition system includes ICP® power, a separate signal conditioner is not required.

ICP® Pressure Sensor

General Purpose Cable

Digital Oscilloscope or DAQ
(External module for ICP® power not shown)

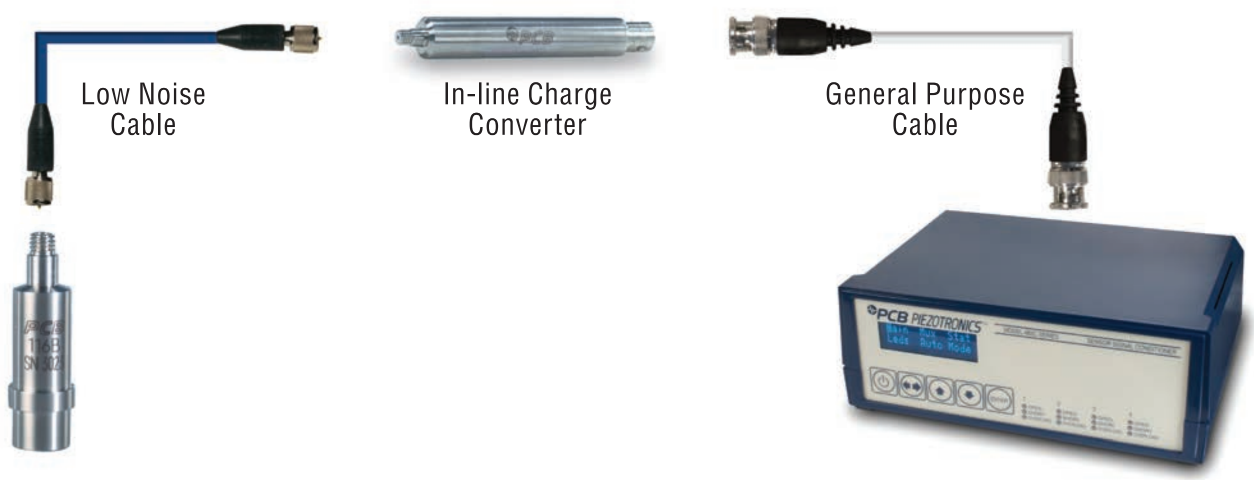
CHARGE PRESSURE SENSOR INSTRUMENTATION

Charge mode pressure sensors' high impedance signal requires conversion to a low impedance voltage signal prior to being processed by data acquisition or readout devices. The conversion can be done in two ways:

Charge Mode Pressure Sensor

Low Noise Cable

Dual Mode Charge Amplifier (Low impedance output to Oscilloscope or DAQ)



Low Noise Cable

In-line Charge Converter

General Purpose Cable

Charge Mode Pressure Sensor

ICP® Signal Conditioner - Powers Charge Converter (Low impedance output to Oscilloscope or DAQ)

MOUNTING & TEMPERATURE CONSIDERATIONS

FLUSH VS. RECESSED MOUNT

- Flush mounting of pressure sensors in a plate or wall is desirable to minimize turbulence, avoid a cavity effect, or avoid an increase in a chamber volume.
- Recessed mounting protects the diaphragm of the pressure sensor from excessive flash temperatures or particle impingement.
- Recessed mounting of pressure sensors will degrade the ability to measure high frequencies as a result of associated cavity resonance.
- Significantly recessed mounting can be useful for attenuation of high frequencies when in the proper proportions, forming a Helmholtz resonator. The Recessed Mount graphic on the right shows a recessed mount with orifice and resonance chamber near the sensor diaphragm.

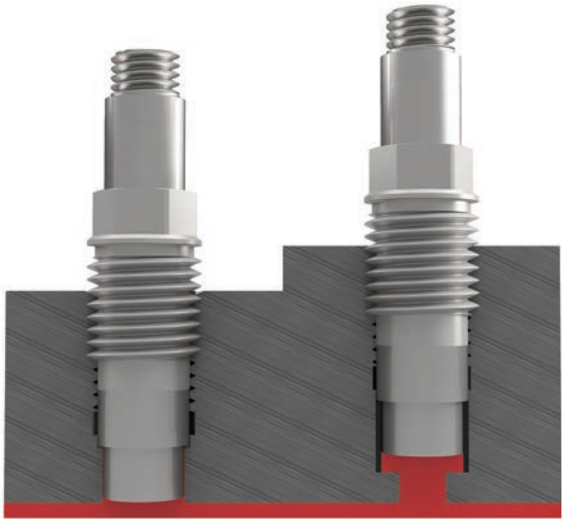
INSTALLATION TIPS

When preparing a mounting port, take care in drilling all diameters concentric to one another. It is important that the side wall of the sensor is not loaded against the mounting wall. This may introduce errors due to the unwanted side load stress.

Always refer to the installation drawings provided before beginning installation procedures.

THERMAL SHOCK

Virtually all pressure sensors are sensitive to thermal shock caused by transient thermal events; hot or cold applied to the diaphragm of a piezoelectric pressure sensor. Internal mechanical preload components can expand, changing the preload applied to the sensing elements, therefore changing the expected sensor output. Thermal shock can be mitigated in multiple ways by utilizing various diaphragm coatings: silicone grease, silicone RTV, vinyl electrical tape, or ceramic coating.



Flush Mount **Recessed Mount**

Helmholtz resonator model, natural frequency (f_n, Hz) for short tube:

$$f_n = [c/(4\pi)][\pi d^2 / (V(L + 0.85d))]^{1/2}$$

where:

c = velocity of sound in the specific media

d = diameter of the tube

V = volume of the lower cavity near sensor face

L = length of the entrance tube

MOUNTING ADAPTORS

Adaptors reduce the need for precision machining in sensor mounting locations where it is impossible, impractical or inconvenient. Threaded mounting adaptors are precision machined to accept PCB pressure sensors and provide a convenient method for sensor installation. A wide variety of metal adaptors are available for general use with select models available in polymers. Polymer adaptors provide ground isolation with the tradeoff of a reduction in operating temperature range and maximum operating pressure. Always confirm the articles under test, sensors, and seals are compatible with test media under the specific test conditions. Some examples of common mounting adaptors are below.

	Model #	Outside Thread	Inside Thread	Hex Size	Material	Description
 	061A01	3/8-24 UNF-2A	5/16-24 UNF-2A	0.625 in	17-4 SS	3/8-24 external thd to 5/16-24 internal thd, 17-4 SS (for Series 111, 112 & 113)
	061A07	M10x1.00-6g	5/16-24 UNF-2A	11 mm	17-4 SS	M10 x 1.0 external thd to M7 x 0.75 internal thd, 17-4 SS
	061A09	3/8-24 UNF-2A	5/16-24 UNF-2A	0.438 in	316 SS	3/8-24-2A external thd to 5/16-24-2B internal thd, 316L SS
	061A10	M10x1.00-6g	5/16-24 UNF-2A	11 mm	17-4 SS	M10 x 1.0 external thd to 5/16-24 internal thd (config to metric 61), 17-4 SS
	061A59	3/8-24 UNF-2A	5/16-24 UNF-2A	0.750 in	Acetal Resin	3/8-24 external thd to 5/16-24 internal thd, Acetal (for Series 111, 112 & 113)
	061M130	7/16-20 UNJF-3A	5/16-24 UNF-2A	0.688 in	17-4 SS	7/16-20 adaptor
	061M145	M14x1.25-6g	5/16-24 UNF-2A	16 mm	17-4 SS	M14 x 1.25 adaptor

ADAPTORS FOR HIGH TEMPERATURE APPLICATIONS

Series 064B Adaptors

Series 123B Pressure Sensors

HIGH TEMPERATURE PRESSURE MEASUREMENT

PCB high temperature dynamic pressure sensors are designed with quartz elements for operation at up to +750 °F (+399 °C) without cooling, typically on compressors and pumps. Water cooled adaptors, as shown above, are available to provide a lower temperature, thermally stable environment that allow sensors to operate in applications above their normal operating range. When cooling isn't feasible, charge mode pressure sensors utilizing UHT-12™ elements operate at up to +1,200 °F (+650 °C).

- Laser welded, hermetically sealed with integral high temperature glass insulated electrical connectors.
- Hardline cables are recommended for operating temperatures above +500 °F (+260 °C). The cable can be welded to the sensor for operation in externally pressurized environments.
- Standard calibration is supplied at room temperature with thermal coefficients provided at various operating temperatures.
- Models with ablative diaphragm coatings are used when media under test reaches flash temperature (ballistic, blast, and rocket motor testing).

Both ICP® and charge pressure sensors can benefit from use of helium bleed and water cooling adaptors. The helium bleed design involves enveloping the case and sensor diaphragm with a steady flow of helium gas coolant. This isolates the sensor from hot combustion gases for a cleaner signal and improved frequency response. Ceramic coatings, combined with pressure adaptors, isolate the sensor from the intense heat in combustion gas streams. See adaptor models 064B01, 064B02, and series 123B pressure sensors for more information.

UHT-12™ is a crystal designed for more accurate, lower noise measurements during large temperature variations and trusted in the most demanding test environments. PCB sensors made with UHT-12™ technology have an improved data quality compared to previous quartz crystal designs.

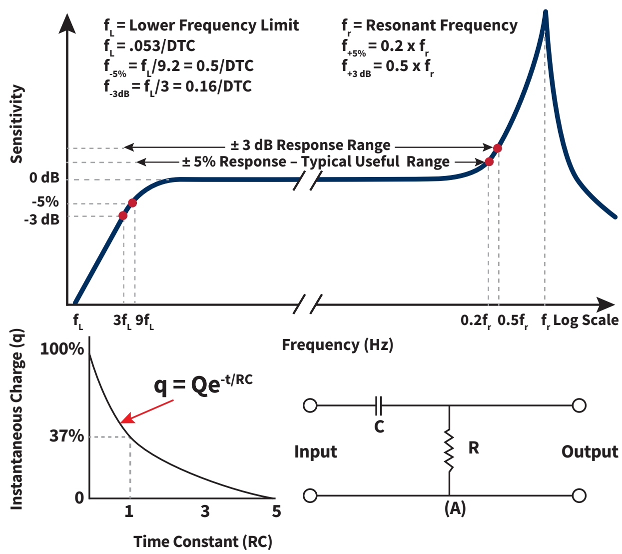
FREQUENCY RESPONSE & RANGE OF ICP® & CHARGE PRESSURE SENSORS

DISCHARGE TIME CONSTANT

- Discharge Time Constant (DTC) is the time (usually in seconds) required for an AC coupled device or measuring system to discharge its signal to 37% of the original value from a step change of measurand.
- Follows RC circuit principles where an instantaneous charge immediately begins dissipating at an exponential rate.
- ICP® sensors have fixed DTC based on the values of the internal RC network. When used in AC coupled systems,(sensor, cable, and ICP® signal conditioner) the sensor will take on the DTC characteristics of the ICP® sensor or signal conditioner (whichever is shortest). In charge mode sensors, the DTC is dictated by choice of charge amplifier or in-line charge converter and system resistance/capacitance.

Where: q = instantaneous charge (pC)
Q = initial quantity of charge (pC)
R = bias (or feedback) resistor value (ohms)
C = total (or feedback) capacitance (pF)
t = any time after t_0 (sec)
e = base of natural log (2.718)

The graphic below shows the relationship between sensitivity and frequency:



HIGH FREQUENCY RESPONSE

Most PCB piezoelectric pressure sensors are constructed with either compression mode quartz crystals preloaded in a rigid housing or unconstrained tourmaline crystals. These designs give the sensors microsecond response times and resonant frequencies in the hundreds of kilohertz, with minimal overshoot or ringing. The mechanical structure of the pressure sensor will impose a high frequency limit with increasing sensitivity as the natural frequency of the sensor is approached.

Measurement error from resonance is avoided by setting a measurement frequency limit - commonly set at 20% of the resonant frequency. Both upper and lower frequency limits must be taken into account to determine appropriate measurement limits for any test (ex: ± 5% or ± 3dB).

LOW FREQUENCY RESPONSE

In ICP® sensors, the low frequency response is dictated by the sensor electronics. Charge mode sensors do not include low frequency response or DTC in their specifications because they are dependent on the specific charge converter or amplifier used. When using charge mode sensors, refer to the specifications of the specific signal converter for low frequency and time constant information.

ICP® sensors have internal microelectronics that perform the conversion from a high impedance charge to a low impedance voltage signal. The low frequency roll off characteristics are included on ICP® sensor datasheets. Example specifications are included in the table on the next page.

TYPICAL PERFORMANCE SPECIFICATIONS

ICP® Pressure Sensor	Model 113B22	
Measurement Range	5,000 psi	34,475 kPa
Sensitivity	1.0 mV/psi	0.145 mV/kPa
Max Static Pressure	10,000 psi	68,950 kPa
Resolution	20 mpsi	0.14 kPa
Low Frequency Response	0.001 Hz	
Upper Frequency Limit	≥ 500 kHz	
Non-Linearity	≤ 1.0 % FS , Zero-based, least-squares, straight line method.	
Environmental		
Acceleration Sensitivity	≤ 0.002 psi/g	≤ 0.0014 kPa/(m/s²)
Temperature Range	-100 to +275 °F	-73 to +135 °C
Electrical		
Output Polarity	Positive with positive pressure	
Discharge Time Constant	≥ 500 sec at room temperature	
Constant Current Excitation	2 to 20 mA	
Output Voltage Bias	8 to 14 VDC	

Charge Pressure Sensor	Model 112B05	
Measurement Range	5,000 psi	34,475 kPa
Sensitivity	1.1 pC/psi	0.16 pC/kPa
Max Static Pressure	10,000 psi	68,950 kPa
Resolution	Determined by external signal conditioning electronics and cable type/length	
Low Frequency Response		
Upper Frequency Limit	≥ 200 kHz	
Non-Linearity	≤ 1.0 % FS , Zero-based, least-squares, straight line method.	
Environmental		
Acceleration Sensitivity	≤ 0.003 psi/g	≤ 0.0021 kPa/(m/s²)
Temperature Range	-400 to +500 °F	-240 to +260 °C
Electrical		
Output Polarity	Negative with positive pressure	
Capacitance	24 pF	
Insulation Resistance	≥1.0 E12 Ohm at room temperature	

EFFECT OF EXCITATION VOLTAGE ON THE DYNAMIC RANGE OF ICP® SENSORS

The specified excitation voltage for all standard ICP® sensors and amplifiers is generally within the range of +18 to +30 volts. The effect of this range is shown in the chart at right.

To explain the chart, the following values will be assumed:

$$VB = \text{Sensor Bias Voltage} = 10\text{ VDC}$$
$$V_{S1} = \text{Supply Voltage 1} = 24\text{ VDC}$$
$$V_{E1} = \text{Excitation Voltage 1} = V_{S1} - 1 = 23\text{ VDC}$$
$$V_{S2} = \text{Supply Voltage 2} = 18\text{ VDC}$$
$$V_{E2} = \text{Excitation Voltage 2} = V_{S2} - 1 = 17\text{ VDC}$$

Note that an approximate 1 volt drop across the current limiting diode (or equivalent circuit) must be maintained for correct current regulation.

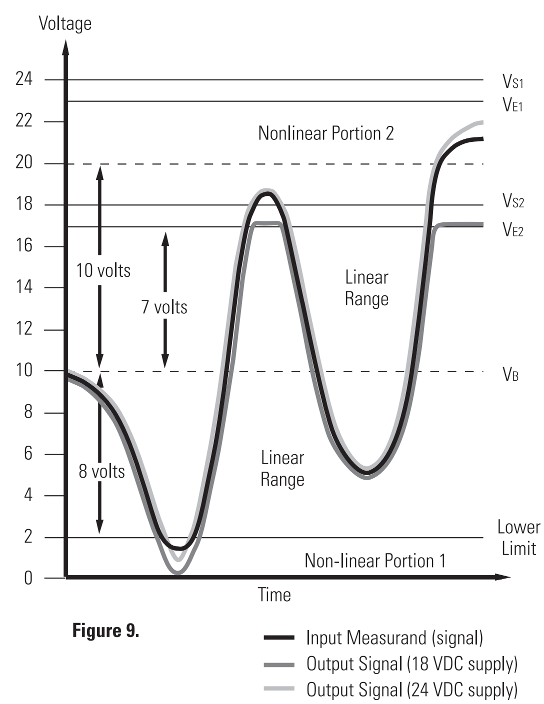
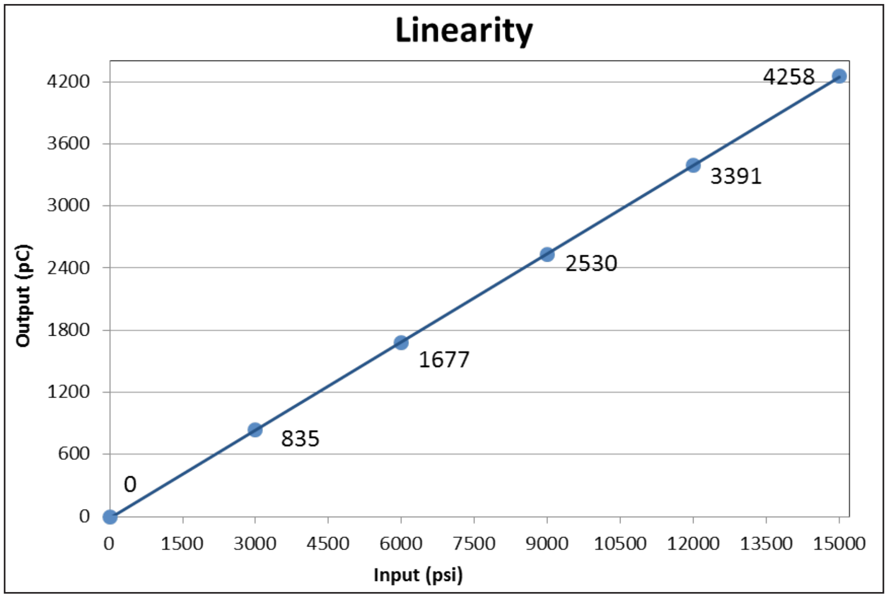


Figure 9.

LINEARITY & CALIBRATION



Linearity (or non-linearity) is defined as the maximum allowable deviation of sensor output versus the input pressure level. This deviation is typically less than 1% of full scale range (FS).

To assure linearity at low pressure levels, some sensors are provided with two calibration certificates:

1.) A full scale output calibration

2.) A 10% of full scale calibration

The low level calibration certificate shows that linearity is still observed at low pressure inputs.

Tabulated input and output information is also typically included on calibration certificates. The data chart below corresponds to the linearity plot to the left.

TEST DATA

INPUT (PSI)	INPUT (kPa)	CHARGE OUTPUT (pC)
3000	20684	835
6000	41369	1677
9000	62053	2530
12000	82737	3391
15000	103421	4258

PIEZOELECTRIC PRESSURE SENSORS MEASURE DYNAMIC PRESSURES:

- Fluctuation & Pulsations
- Fluid Born Noise
- High Intensity Sound
- Acoustics & Buffering
- Troubleshooting - frequency content
- Wind Tunnels
- Blast Waves & Time of Arrival
- Ballistic Testing
- Engine & Cylinder Combustion
- Rocket Motor Engines & Fueling
- Underwater Blast
- Localized Cavitation
- Hydraulics & Pneumatics
- Waterline Acoustics
- Subsea Characterization

AMPLITUDE RANGE OF PCB PRESSURE SENSORS

Most ICP® pressure sensors have a full scale output of ±5 volts at a specific pressure value. Charge sensors full scale output will also be at a specific pressure, only in picocoulombs (pC). Both types exhibit a sensitivity in either millivolts or picocoulombs per unit of pressure and can operate anywhere within the measurement range listed on the specification sheet. Charge output sensors will require an additional charge amplifier or charge converter. Laboratory charge amplifiers typically have the ability to adjust gain and measurement range. In-line charge converters typically have a fixed conversion value and maximum output limit.

ICP® Measurement Output

Pressure Sensitivity (PS): 1.0 mV/psi

Measurement Range (MR): 5,000 psi

Signal Output (V_{out}) = PS x MR

= 1.0 mV/psi x 5,000 psi

V_{out} = 5,000 mV = 5.0 volts

Charge Measurement Range

The max force measurable with this sensor and converter combination

Pressure Sensitivity (PS): 1.1 pC/psi

Converter Input Range (CI): ± 5,000 pC

Measureable Pressure (MP_{max}) = CI ÷ PS

= ± 500 pC ÷ 1.1 pC/psi

= ± 5,000 pC ÷ 18 pC/lb

MP_{max} = 4,545 psi

(Vacuum requires special consideration)

Charge Gain Conversion

Pressure Sensitivity (PS): 1.1 pC/psi

Pressure Input (P_{In}): 3,000 psi

Charge Conversion (CC): 1.0 mV/pC

Signal Output (V_{out}) = 1.1 pC/psi x 3,000 psi x 1.0 mV/pC

= 18 pC/lb x 75 lb x 1.0 mV/pC

V_{out} = 3,300 mV = 3.3 volts

Conversion Units

1 psi (lb/in^2) = 0.0689 bar = 6.895 kPa

1,000 psi (lb/in^2) = 68.95 bar = 6.895 MPa

ADVANCED PRESSURE APPLICATIONS

CAVITATION & FATIGUE ANALYSIS

Cavitation is the formation of bubbles in a liquid, typically by the movement of a propeller through it. PCB's sub-miniature dynamic pressure sensors (105C) are small enough for installation where space is limited. These dynamic pressure sensors are designed specifically to fit into critical locations in pump and valve housings to measure flow disturbances or peak pressure pulses.

- Integral machined diaphragms for long life
- Quartz element has fast rise time of 2 microseconds
- High resonant frequency exceeding 250 kHz

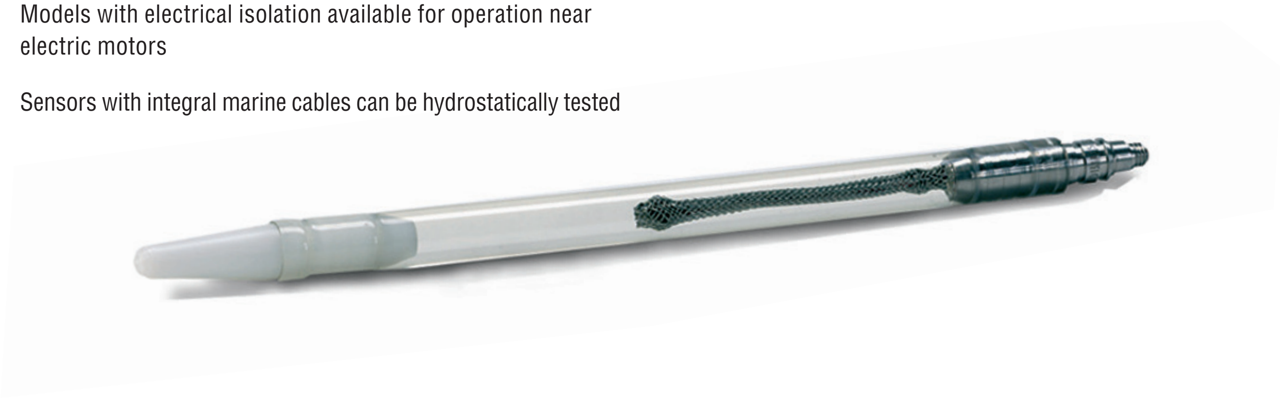
UNDERWATER DISTURBANCES

Piezoelectric pressure sensors are suited for dynamic pressure measurements underwater including blast, turbulence, and cavitation.

These measurements require a fast rise time, ruggedness, and high stiffness in order to obtain a high frequency response.

Flush mounting of pressure sensors is especially important when measuring unsteady flow on the external surface of a vessel. Two key features for underwater use include electrical isolation and integral over-molded cable assemblies.

- Models with electrical isolation available for operation near electric motors
- Sensors with integral marine cables can be hydrostatically tested



BALLISTICS & PROPELLANT

PCB conformal pressure sensors measure ballistic chamber pressure, for ammunition batch qualification testing, directly through the side of an unmodified cartridge or shell casing wall. An adaptor closely resembling the test barrel with cartridge and sensor installed is used to calibrate and determine the effect of the shell case on sensor sensitivity. PCB pressure sensors can be used in various configurations: modified cartridge cases, chambers with specially aligned pressure porting, or directly in the barrel just beyond the chamber.

- ANSI/SAAMI Standard Z299 specifies PCB Conformal Pressure Sensors
- Case Mouth Pressure Sensors
- Ballistic pressures up to 100,000 psi (6,900 bar, 689 MPa)

EXPLOSIVE & BLAST

Specially designed pressure sensors are used for a wide range of airborne explosion, blast, and shock wave tests. The rise time and frequency ranges are tailored to capture both peak pressure, total impulse, time of arrival and Mach number measurements. The pressure sensors are used to study blast effects on structures, vehicles, and other objects.

- Free-field – Open Air Blast
- Mining and construction blasting
- Multi-sensor configurations for Mach number measurement

Quartz, Free-field, ICP® Blast Pressure Pencil Probe with 2 Outputs for Time of Arrival Measurement

SPECIFICATIONS					
Model Number	**137B25**	**137B26**	**137B27**	**137B28**	**137B32**
					Rear Sensor is placebo
Sensitivity (±15%)	100 mV/psi 14.5 mV/kPa	20 mV/psi 2.90 mV/kPa	10 mV/psi 1.45 mV/kPa	1 mV/psi 0.145mV/kPa	20 mV/psi 2.90 mV/kPa
Measurement Range	50 psi (4.45 bar, 345 kPa)	250 psi (17.24 bar, 1724 kPa)	500 psi (34.47 bar, 3447 kPa)	1000 psi (68.95 bar, 6895 kPa)	250 psi (17.24 bar, 1724 kPa)
Frequency (± 5%)	≥ 400 kHz				
Incident Rise Time	≤ 6.5 µsec				

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